DEVELOPMENT OF A PROCEDURE TO NONDESTRUCTIVELY EVALUATE THE FUSION QUALITY OF GEOMEMBRANE SEAMS

RMD Report L-93

Alberta
ENVIRONMENT
Environmental Protection Services
Research Management Division

RESEARCH MANAGEMENT DIVISION EMBLEM

The Emblem represents the interdisciplinary and holistic nature of the Division's environmental research programs. Each of the five sections of the symbol represent comprehensive programs on air, water, land, humans and their constant interaction. The sections converge to form a cohesive chain, characteristic of an effective research organization. This cohesive bonding makes the sections blossom into the environment in the form of a flower — an Albertan wild rose.

DEVELOPMENT OF A PROCEDURE TO NONDESTRUCTIVELY EVALUATE THE FUSION QUALITY OF GEOMEMBRANE SEAMS

RESEARCH MANAGEMENT DIVISION
Alberta Environment

For information on reports published by the Research Management Division, contact:

Research Management Division
Publications Office
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta
T5J 3N4

(403) 427-3946

This report may be cited as:

Peggs, I.D., and D. Little. 1986. Development of a procedure to nondestructively evaluate the fusion quality of geomembrane seams. Prep. for Alberta Environment, Research Management Division by Hanson Materials Engineering. RMD Report L-93. 77 pp.

DEVELOPMENT OF A PROCEDURE TO NONDESTRUCTIVELY EVALUATE THE FUSION QUALITY OF GEOMEMBRANE SEAMS

by

I.D. PEGGS
D. LITTLE

Hanson Materials Engineering
Edmonton

for

RESEARCH MANAGEMENT DIVISION
Alberta Environment

RMD Report L-93

1986

EXECUTIVE SUMMARY

Considerable inconsistencies are found in the quality of field-prepared seams in geomembrane installations manufactured from synthetic materials such as polyvinyl chloride (PVC) and high density polyethylene (HDPE). Conventional nondestructive inspection techniques are limited to specific seam geometries and will not detect defects that, although they are not immediately critical, may propagate during service into critical defects, thus causing premature lining failure.

The objective of this project was to develop a novel ultrasonic technique that would monitor changes in frequency and amplitude distributions of a multi-frequency signal as it passes through the seam interfaces. The technique developed is a dry-scan technique that does not need a fluid couplant between the transducer and the component being inspected, and the separate transmitting and receiving transducers can be in the form of wheels that can be mounted in a carrier astride the seams and traversed along the seam potentially at walking speed.

Several different seam geometries and qualities in PVC and HDPE geomembranes were evaluated by this technique and where "defects" were indicated, specimens were removed for conventional mechanical shear and peel testing augmented by microstructural examination of thin-slice microtome sections prepared from the seam cross-section.

A detailed evaluation of a series of variable quality extrusion fillet seams in a 2 mm thick HDPE geomembrane facilitates the development of a specific procedure to inspect such seams on a production basis. Relatively minor changes will be required for recalibration to other thicknesses and other unsupported materials.

While the technique was proven to be capable of detecting lack of fusion, cold fusion, laminar defects within the membrane itself, porosity and small particulates, the nature of the defect (other than gross lack of fusion and cold fusion) cannot yet be determined from the profile of the signal. However, we feel that such definition ultimately will be possible.

It is evident that the technique is capable of detecting defects that do not adversely affect the serviceability of the liner installation, hence a major effort is required to define sizes and distributions of critical defects in the different seam geometries.

The ultrasonic flaw detection technique can be applied immediately to field inspections of extrusion seams in HDPE geomembranes of 1 mm and greater thickness.

A booster is required to inspect seams in 0.5 mm thick PVC and HDPE. A booster is also required for double-track thermal seams in HDPE of all thicknesses.

TABLE OF CONTENTS

continued . . .

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

ABSTRACT

An ultrasonic technique employing dry-scan wheel transducers has been used to develop a technique for the rapid inspection of field-prepared seams in PVC and HDPE geomembranes and flexible membrane liners.

The membrane is saturated on one side of the seam with ultrasound at frequencies between 0.1 and 3 MHz. As the sound passes through the fusion zone the modified signal is monitored on the opposite side of the seam. Lack of fusion, cold fusion, porosity, and particulate defects can be detected.

Since the technique does not require direct contact with the seam itself, it is applicable to all seam geometries and thus provides inspection capability for extruded fillet seams.

A specific procedure for the inspection of extruded fillet seams in 2 mm thick HDPE is described.

ACKNOWLEDGEMENTS

The author wishes to thank Alberta Environment for the funding for this project, Alberta Environment and the Alberta Research Council for the provision of PVC samples, and Gundle Lining Systems and Schlegel Lining Technology for the provision of HDPE samples.

1. INTRODUCTION

1.1 GENERAL

With increased attention being given to environmental protection and the necessity to prevent groundwater contamination, there is a burgeoning growth in the use of plastic sheeting, or geomembrane, as an impermeable barrier to contain undesirable contaminants in fluid waste impoundments, hazardous waste sites, and the like.

Conversely, such geomembranes are also used to conserve fresh water supplies by lining irrigation canals and reservoirs to minimize leakage into the ground and by covering potable water reservoirs to minimize evaporative losses and surface contamination.

The geomembrane itself can be considered "impermeable" provided it is not mechanically damaged during installation, but the Achilles heel of such a system is and will continue to be the field seams, which are necessary in the vast majority of installations.

Seams must not leak.

In installations covering areas of 10^5 to 10^6 m^2, which are commonly being constructed, a failure rate of 0.001% of the seam length just is not acceptable. Extremely thorough inspection techniques during field seaming are thus of prime importance, both to detect areas of seams that have not been joined and will leak immediately, and to define those areas that will not leak immediately but will develop leaks during service.

Conventionally, seams are inspected or tested by three techniques:

1. Visual inspection;
2. Mechanical tests on cut-out samples; and
3. Nondestructive techniques such as vacuum box, air lance, and ultrasonic.

Visual inspection may provide 30% assurance of acceptable seam quality, with nondestructive techniques providing an additional 30% assurance. Mechanical testing also contributes 30%, but requires that repair

patches be installed to replace the cut-out samples. Mechanical test samples can thus never be used to completely assure seam quality.

Increasing the efficiency and capabilities of nondestructive inspection techniques is the logical approach for improving the status quo. The various techniques will be described in detail later, but new developments in ultrasonic equipment offer significant potential for evaluating joints in polymeric materials.

The objective of this project is to evaluate this new ultrasonic technology and to develop a technique for the evaluation of field-prepared seams in synthetic geomembranes.

1.2 MEMBRANE MATERIAL

A general survey of membrane materials and their applications has recently been issued by Alberta Environment (Penttinen 1984). The predominant materials in use in Alberta are polyvinyl chloride (PVC) and high density polyethylene (HDPE). The former is used as a liner for irrigation canals and the latter for most other applications, such as liners for sewage lagoons and fluid waste impoundments. PVC is usually used at thicknesses of 0.5 or 0.75 mm, while HDPE ranges from 0.5 to 2.5 mm, most frequently being 1.5, 2.0, or 2.5 mm thick. PVC is generally covered to protect against UV radiation, but HDPE may be exposed to the environment and as such is subject to a large amount of thermal contraction during periods of low temperature. To avoid excessive stresses across the seams, sufficient slackness must be built into the liner to accommodate contraction with minimal induced stresses.

Because of the relative rigidity of seams and geometrical changes in profile associated with them, stress concentrations can develop within seams as the membranes are loaded. Careful attention to potential stress concentrating geometries is required during inspection to identify those features that may cause problems during service. The plastic pipe gas distribution industry has concentrated a great deal of work on long-term brittle fracture mechanisms, such as slow crack growth, in HDPE pipe (Bell et al. 1983).

The general scope of this study will thus include both PVC and HDPE geomembrane seams, with the emphasis being placed on the latter due to their predominance in practical applications and their range of different seam geometries that affect the applicability of conventional nondestructive techniques.

1.3 SEAM GEOMETRIES

The seams in PVC geomembranes all show the same cross-sectional geometrical profile (Figure 1), but the method of joining varies -- thermal fusion or adhesive cement or solvent adhesive.

The only method of joining HDPE is by thermal fusion, and this can be achieved with or without the addition of a bead of extruded HDPE of the same resin as that used for the geomembrane. The HDPE seam geometries are shown in Figure 2.

In all cases the objective of seaming is to produce a joint that is as strong as the base membrane itself. Mechanically, this is evaluated in two ways, as shown in Figure 3:

1. Tensile shear test across the seam and
2. Peel test.

The shear test evaluates the ability of the seam to tolerate instantaneous service stresses in the plane of the liner, while the prime intent of the peel test is simply to evaluate the degree of fusion. The peel test is the more meaningful test to evaluate fusion/seam quality. In fact, it does represent some field stresses that can affect the integrity of the seam over extended periods of time.

Defects such as lack-of-fusion (LOF) at the interface, voids or dirt particles on the interface, and cold fusion can all produce peel test failures (Figure 4), and may be the cause of leaks during service.

Cold fusion occurs when the two surfaces have fused together to eliminate an actual interface, but where crystallite growth has not developed to the extent required to produce maximum strength.

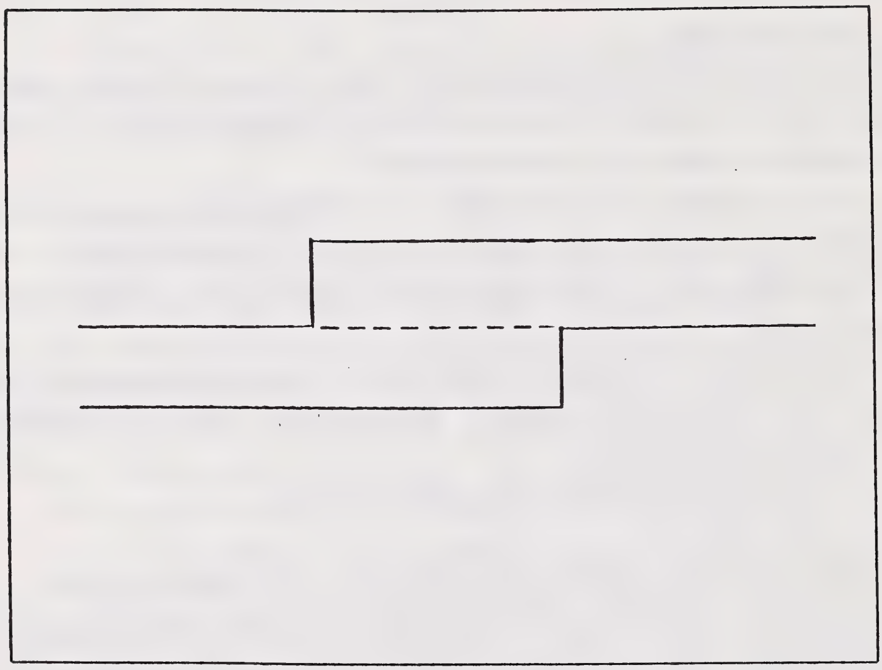


Figure 1. Schematic of all PVC seams.

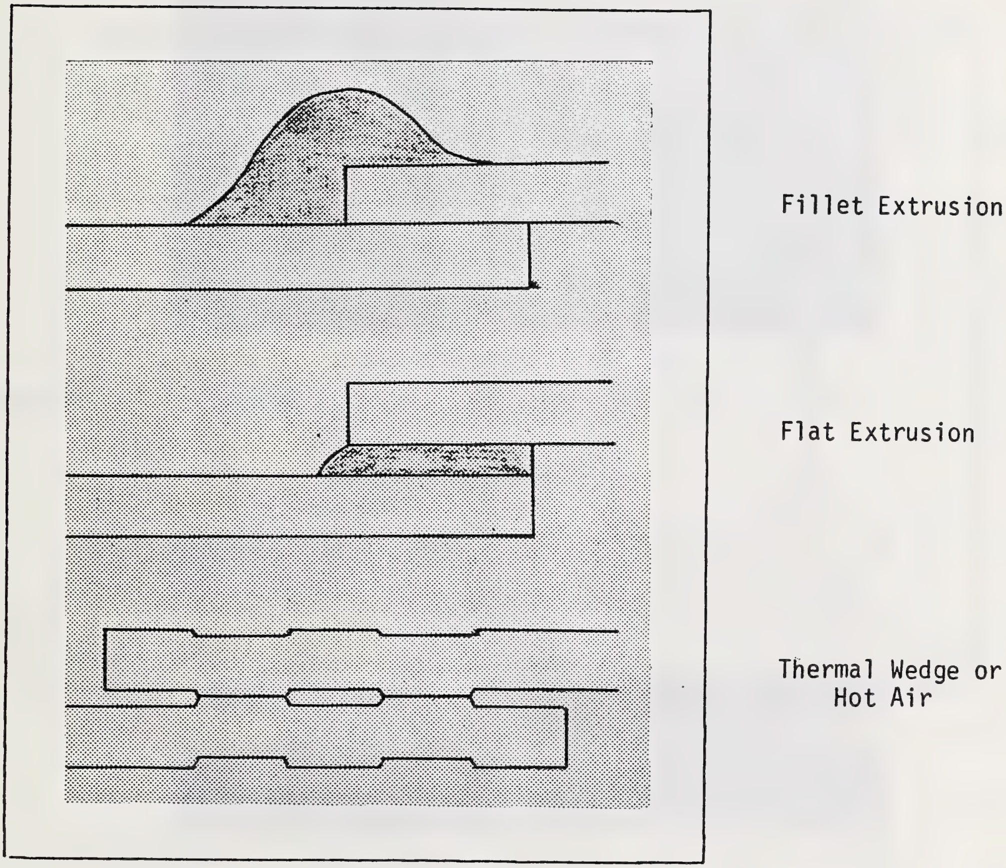


Figure 2. Schematic of HDPE seams.

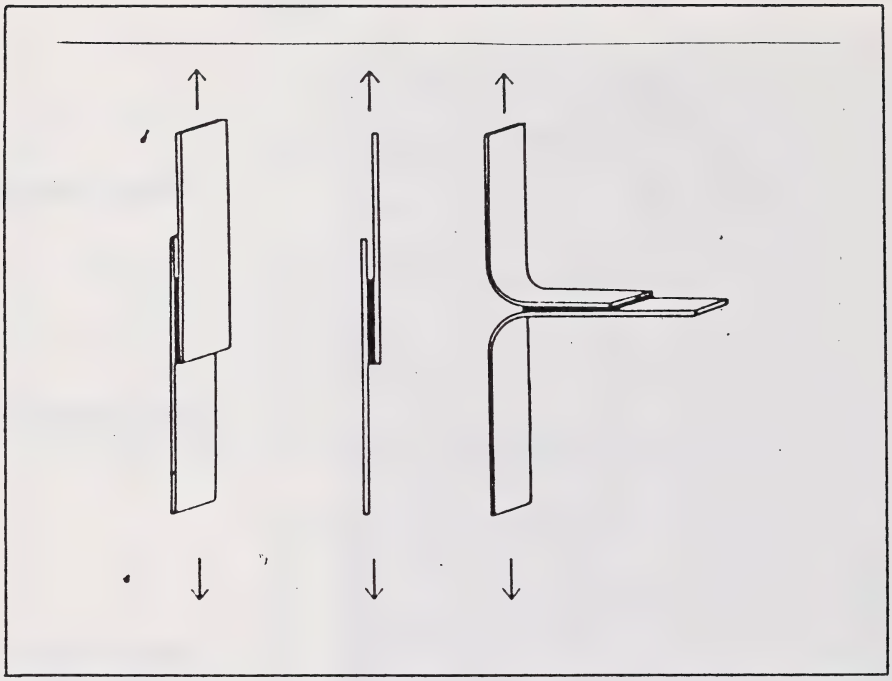
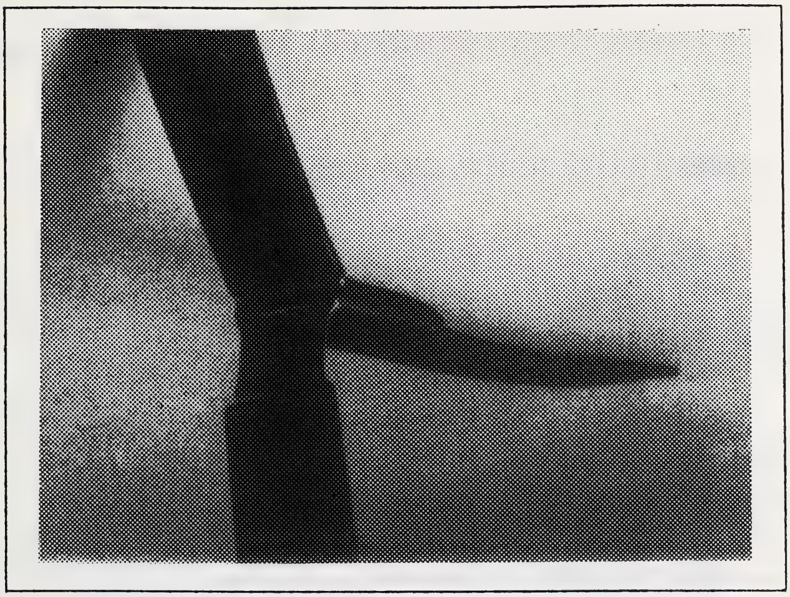


Figure 3. Orientation of tensile shear and peel specimens.



Acceptable peel test on flat extrusion seam - the membrane fails.

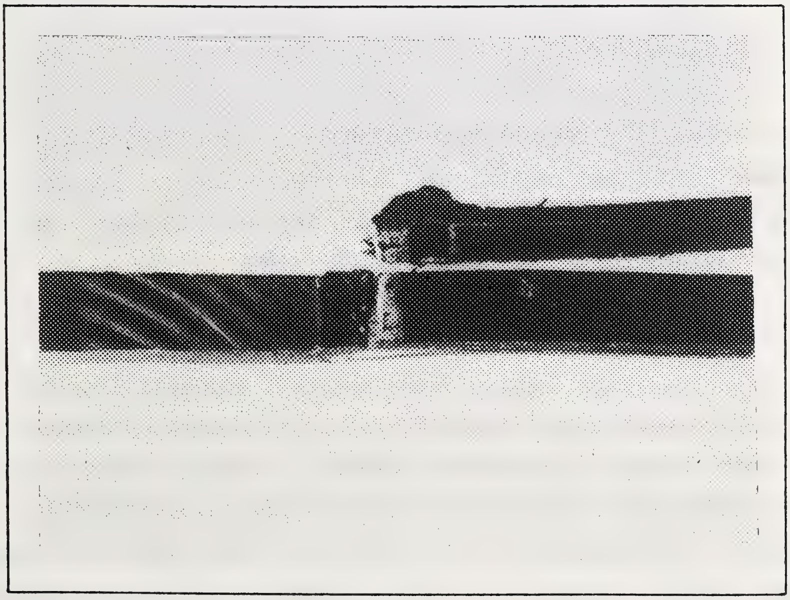


Figure 4. Peel separation of extrusion fillet seams.

Cold fusion is the most difficult state to detect by nondestructive methods.

1.4 NONDESTRUCTIVE TESTING TECHNIQUES

1.4.1 Vacuum Box

A soap solution is spread along the seam and covered by a long box with a transparent top in which a vacuum is drawn. Bubbles in the soap solution will identify a through-seam leak.

This technique will not identify a location where there is a channel most of the way through a seam but where a small amount of fusion causes it to be blocked. The stress concentrations at this defect in service could cause it to open up and produce a leak in a relatively short period of time. The step-by-step inspection procedure using a vacuum box, with its attendant large volume of soap solution and vacumm lines, makes it a cumbersome 100% inspection technique.

1.4.2 Air Lance

A jet of pressurized air is directed at the exposed edge of the seam. If there is a through-seam channel, or an exposed lack of fusion and an adjacent cold fused region, the seam may separate. However, if the seam is fused at the exposed edge (Figure 5), the air lance will not detect any defective regions that may lie within the seam.

1.4.3 Air Pressure

The hot wedge seaming technique that produces parallel fusion tracks with a void between them (Figure 6) can be inspected by pressurizing the central void through a hypodermic needle. A leak is defined if pressure cannot be maintained. This method is difficult to use on thick membranes and at times when the membrane is cold and more rigid. Modifications of this technique include putting in a larger volume of air at the exposed end of the seam to locate leaks audibly, and to put helium into the void to locate leaks with a helium leak detector.

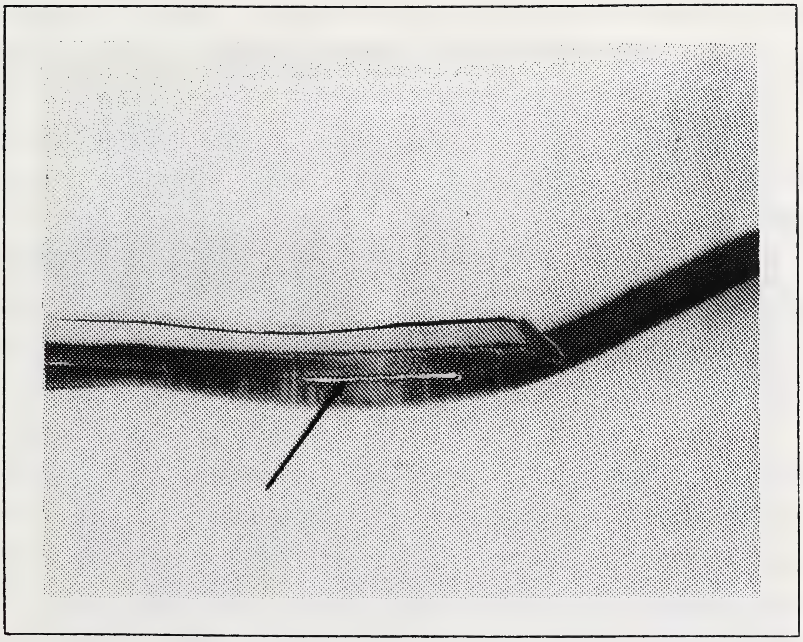


Figure 5. Lack of fusion in centre of flat extrusion seam.

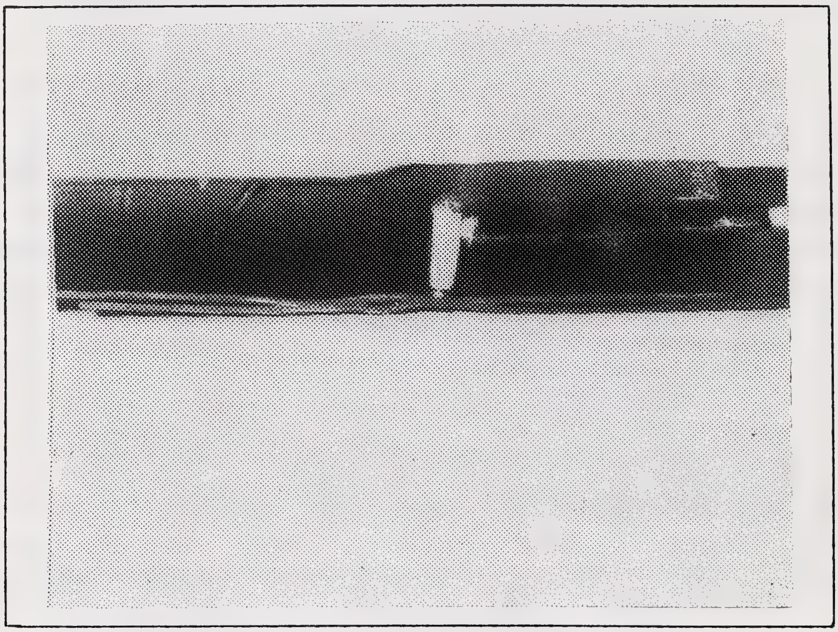


Figure 6. Double hot wedge thermal seam showing central void.

This technique will, again, only detect existing through leaks and not potential leaks.

1.4.4 Ultrasonics

Conventional ultrasonic techniques are based on the principle of transmitting an ultrasound signal of known frequency through a material in which the speed of sound is known, then picking up the reflection of that signal when it bounces off any surface in its path. The time-of-flight of the signal is thus converted into a distance measurement, and the location of the reflective surface can be identified.

In an homogeneous sheet, the only reflection will be produced by the back, or bottom surface (Figure 7). If two sheets are laid together and fused at the interface, the only signal will again be produced by the back surface, but the time-of-flight will be twice that in the single sheet. If an intermediate signal is received in addition to the bottom surface signal, there are voids or particulates reflecting some of the signal back while the remainder goes through to the back face (Figure 8).

In effect the ultrasonic equipment is being used as a thickness meter. An alarm gate can be established where the interface signal will occur if defects exist on the interface to provide an audible alarm. The technique is thus capable of "mapping" the extent of any defect and does not depend on the defect being exposed to the environment. A large internal defect can be identified and repaired. Alternately, a questionable indication can be cut out for mechanical testing.

Transducers used for this pulse-echo technique are conventionally upward of 5 mm in diameter, with a split surface for separate transmitting and receiving functions (Figure 9). The complete surface of the transducer must maintain a uniform air-free contact with the surface of the membrane. This is usually achieved with fluid couplant such as grease, cellulose/water mixture (wallpaper paste), or simply water. The fluid must of course be compatible with the liner so as not to induce environmental stress cracking. Glycol can be mixed with the water for testing in cold temperatures.

There are a few practical problems in applying this ultrasonic technique to geomembrane seams:

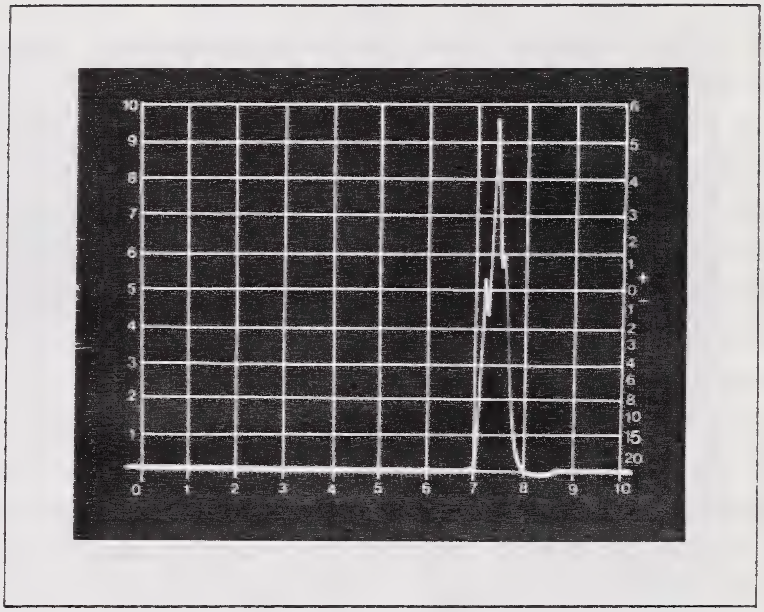


Figure 7. Ultrasonic reflection from acceptable fusion.

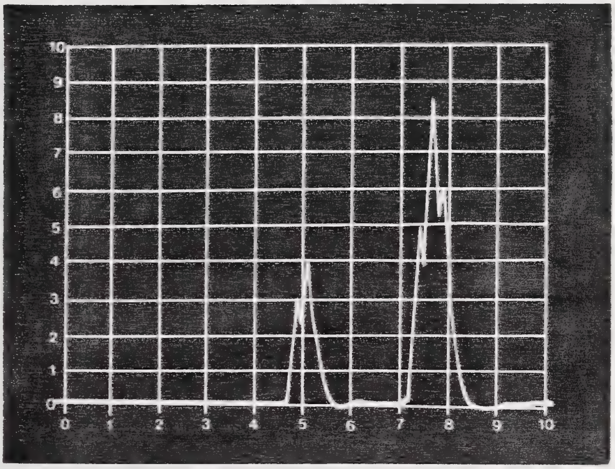


Figure 8. Ultrasonic echoes indicating partial fusion at interface.

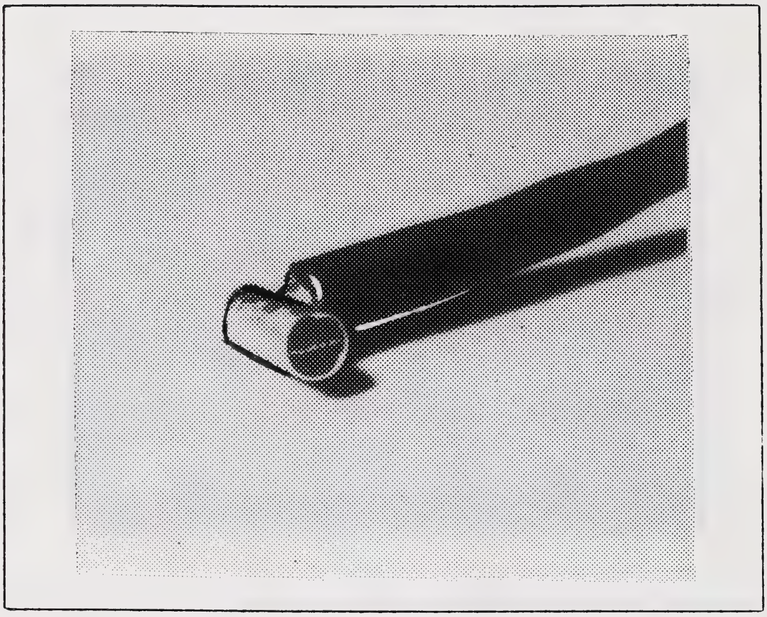


Figure 9. Conventional ultrasonic transducer.

1. Carrying and uniformly applying a large amount of couplant without trapping air,
2. Sliding the transducer along the membrane, and
3. Ensuring that the full width of the seam is covered without getting spurious signals from the edge.

Additionally, since complete surface contact is required, the technique cannot be used on seams where an extruded bead is deposited over the edge of the overlapping sheet (Figure 10), and cold fusion cannot be detected (further explanation follows).

The signal transmitted through the sample is at a specific frequency, usually in the 1 to 5 MHz range, and the return signal is also detected at the same frequency. The time-of-flight is recorded to identify the location of the reflective interface between solid material and air or two solids of different densities. At a cold fused surface there is no distinct interface. While there may be local changes in density, they are insufficient to produce a significant reflection at the same frequency of the input signal. However, the input signal is undoubtedly modified when passing through a zone of incomplete fusion, and thus a spectrum analyser capable of presenting the amplitudes of a range of frequencies should be able to identify the modified transmitted signal. While a modified signal may be reflected from a zone of cold fusion or from small voids or particulates at the interface, the identification of changes in a transmitted signal will be much easier to measure. Evaluations along these lines have been performed on butt fusions in HDPE natural gas distribution pipe (House and Lustiger 1983; Badgerow 1983). The butt fusion of pipe is very similar to fusions in membranes, as the prepared ends of two pieces of pipe are simply heated to appropriate temperatures and butted together, allowing the two layers of molten material to mix together and solidify as one.

The studies at the Battelle Institute (House and Lustiger 1983) use the pitch-catch technique of inputting single frequency ultrasound into the pipe on one side of the joint and catching it on the opposite side after it has been modified by the fusion zone. The signal data is monitored by computer and the joint accepted or rejected.

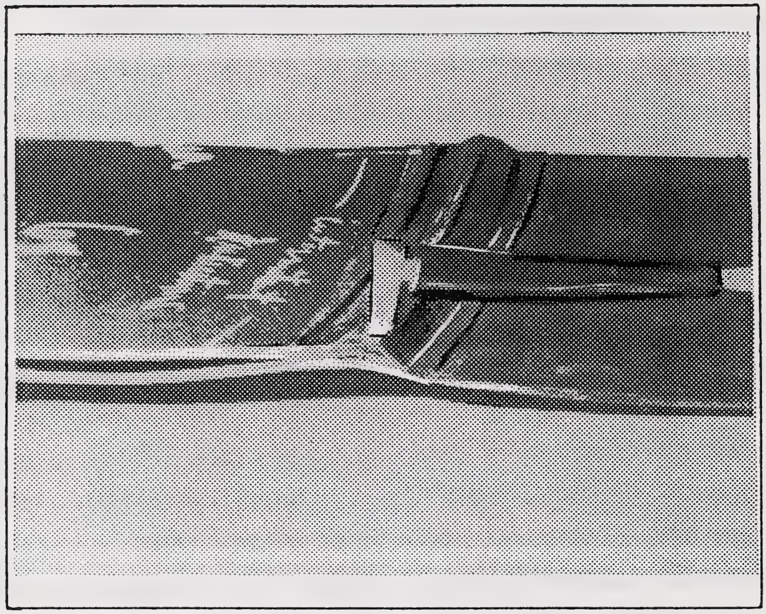


Figure 10. Conventional transducer cannot maintain good contact with extruded fillet seam.

The technique used by Wisconsin Gas (Badgerow 1983) employs an ultrasonic flaw detector that transmits an ultrasonic signal consisting of a range of frequencies through the fusion zone, and monitors both the time delay and profile change of the signal. It is claimed that this technique is capable of detecting cold fusions. An added advantage of this particular equipment is that it uses soft-tip probes that require no couplant. In addition, wheel transducers are available that require no couplant. The transmitting transducer would thus be rolled along one edge of the seam and the receiving transducer rolled adjacent to it on the other side of the seam, both on the top surface of the liner, thus analysing the seam at much higher speeds than are currently practical.

The general approach of the present study is thus to assess the applicability of the flaw detector-type equipment in evaluating PVC and HDPE geomembrane seams and to develop procedures for its use in field installations.

2. MATERIALS AND METHODS

Materials and sample seams for evaluation were generously supplied by Alberta Environment (PVC), Gundle Lining Systems (HDPE), and Schlegel Lining Technology (HDPE). Additional samples were available from the archives of Hanson Materials Engineering.

All PVC samples were 0.5 mm thick. Three joining techniques were used: thermal, solvent adhesive, and dielectric. The latter is an electrical in-plant technique used to prepare large sheets for field installation. It is not a method used in the field. All different types of HDPE seam geometries were evaluated on membranes 0.5, 1.5, and 2.0 mm thick.

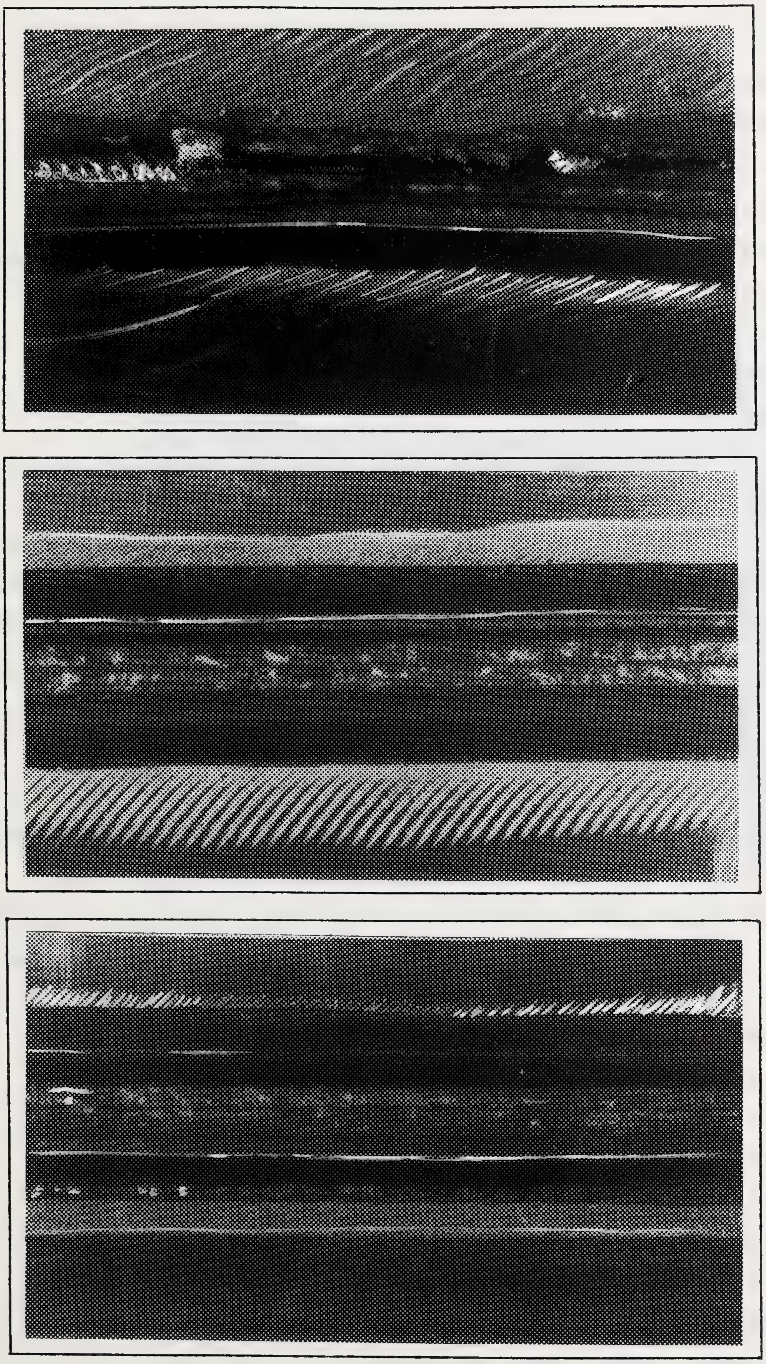
Several of the supplied samples were prepared to have seams of acceptable, rejectable, and indifferent quality (**Figure 11**), but the nature of any defect is not known to us.

After the samples were evaluated ultrasonically and control settings recorded, the seams were destructively examined to determine the reasons for the observed signal changes and indications. Method used were:

1. Mechanical peel and shear tests to relate the ultrasonic indications to observations typically made on field test specimens, and
2. Transmitted light microscopy of microtome sections removed from cross-sections of the seams. Microtomes are thin slices of material between 10 and 20 μm thick (Bell and Cook 1979).

Mechanical tests were performed on strip specimens 25 mm wide according to US National Sanitation Foundation Standard #54 and, in the case of the Gundle Seams, which are only 20 mm (approx.) wide, on ASTM D638 Type M1 specimens. All specimens were stamped from sheets with dies. When defects were localized, narrow specimens were cut with a utility knife. The elongation rate for both shear and peel tests was 50 mm/min. Tests were performed on Instron or Tinius Olsen testing machines. Parameters that were monitored, not necessesarily for every specimen, were:

1. Shear Test - bonded seam strength, $P_1/(W.t)$
   - elongation l/lo
2. Peel Test - peel strength, $P_2/(W.t)$
   - peel separation, X/Xo



Poor

Indifferent

Good

Figure 11. Poor, indifferent, and good quality extrusion fillet seams.

where

P_1 = maximum load in shear test

P_2 = maximum load in peel test

W = width of specimen (25 mm nominal)

t = thickness of membrane

lo = one half of length of single thickness membrane within gauge length

l = elongation at failure

Xo = width of seam

X = length of seam separation

All fracture faces and peel separation faces were examined microscopically. Specimens should fail in the membrane adjacent to the seam.

Microtomes were prepared with a simple microtome knife mounted on a small custom-modified milling machine. Microtomes were mounted between two glass microscope slides with balsam cement and examined on the Olympus MPE Metallograph. Microtomes reveal features such as the extrusion flow pattern in the membrane (Figure 12), the width of the fusion zone (Figure 13), the displaced molten material (Figure 14) and, when crossed polarizing filters are inserted in the light path before and after the specimen, the distribution of residual stresses (Figure 15). The use of polarized light also aids in the identification of small crazes and cracks (Figure 16).

In addition to the flaw detector, a conventional ultrasonic machine and transducer were used. The machine was a Krautkramer USM-2 with a zero degree 5 mm diameter pulse/echo transducer at a frequency of 5 MHz. The flaw detector was a Balteau Sonatest unit model UFDS-2 with 5 mm diameter soft-tipped probes and 25 mm diameter wheel probes.

The peak frequency response of these transducers is centred about 0.5 and 1.25 MHz respectively. The unit and its controls are shown in Figure 17, the wheel transducers in Figure 18. A typical output signal from homogeneous, nondefective membrane is shown in Figure 19. It should be noted that time is on the horizontal scale and signal amplitude on the vertical scale. The signal is much broader and contains more information than the single frequency signal shown in Figure 7.

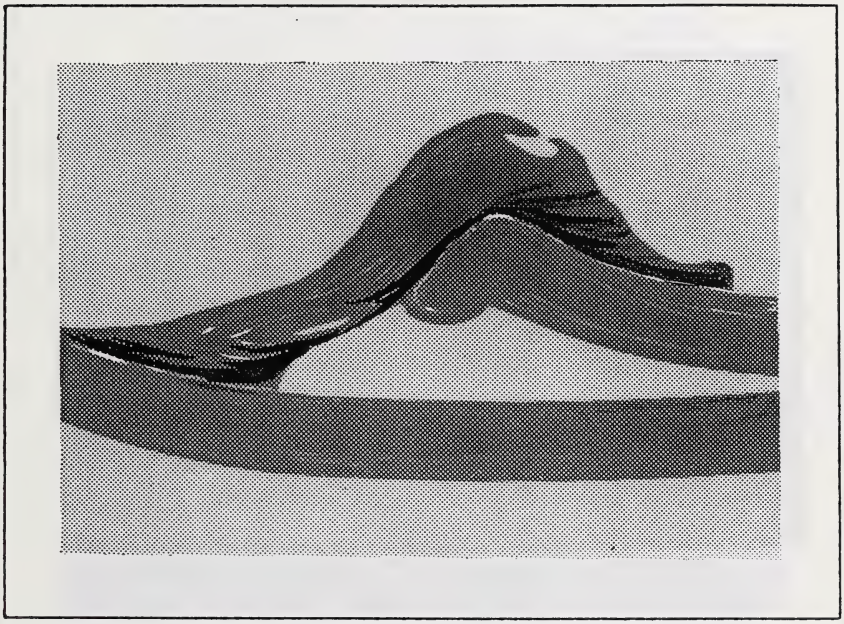


Figure 12. Microtome of fillet seam showing flow patterns in liner and extrudate.

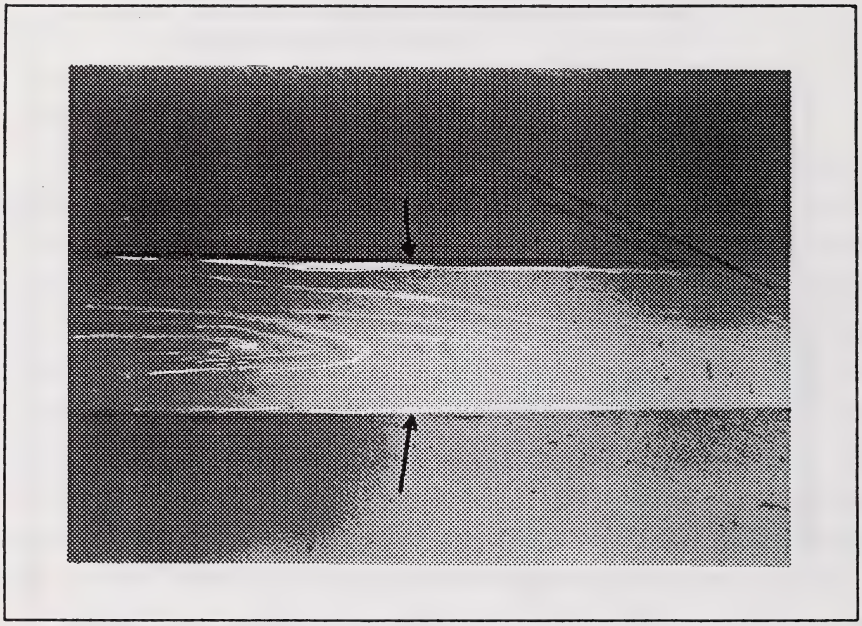


Figure 13. Fusion zone in flat extrusion seam.

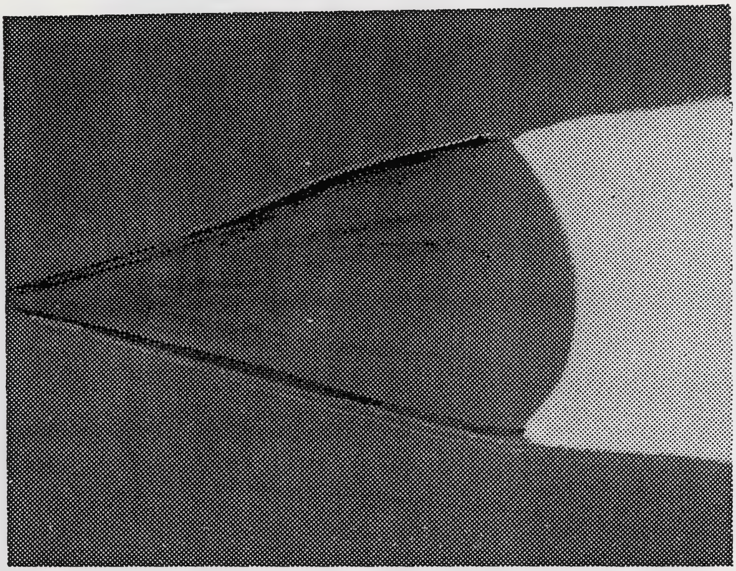


Figure 14. Extrusion bead at edge of thermal seam.

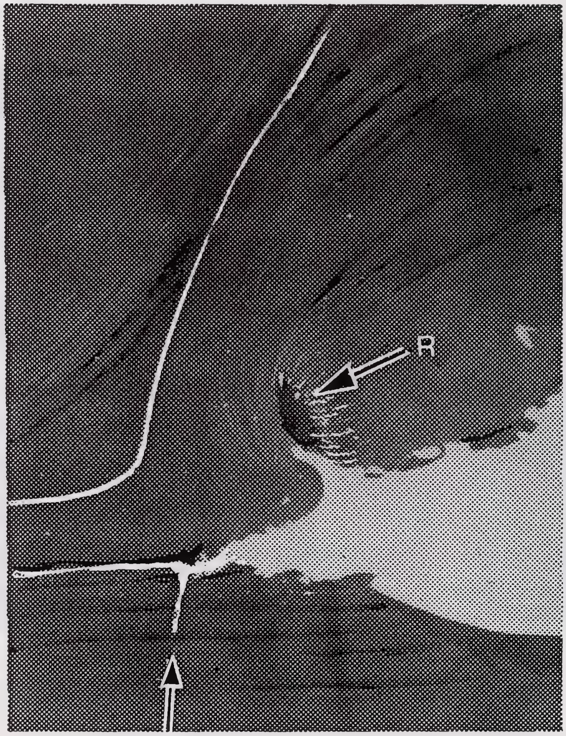
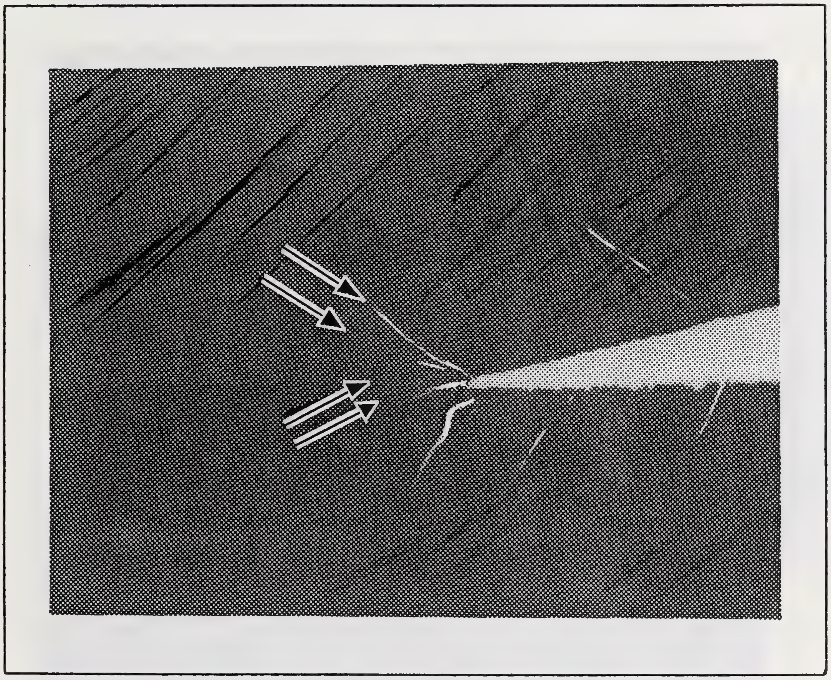


Figure 15. Residual stress and crazing at end of top sheet in fillet.



Mag. X 50

Figure 16. Crazing at tip of peel separation.

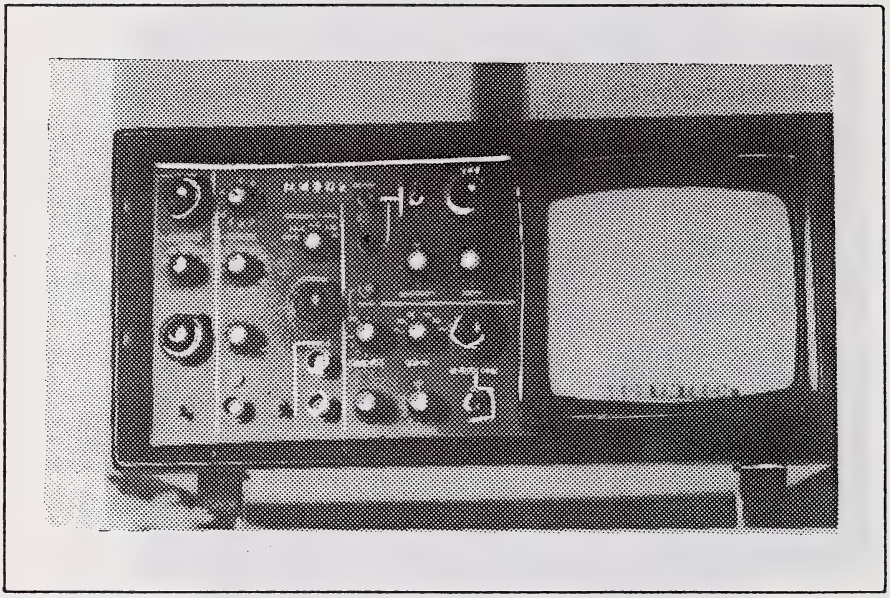


Figure 17. Ultrasonic flaw detector.

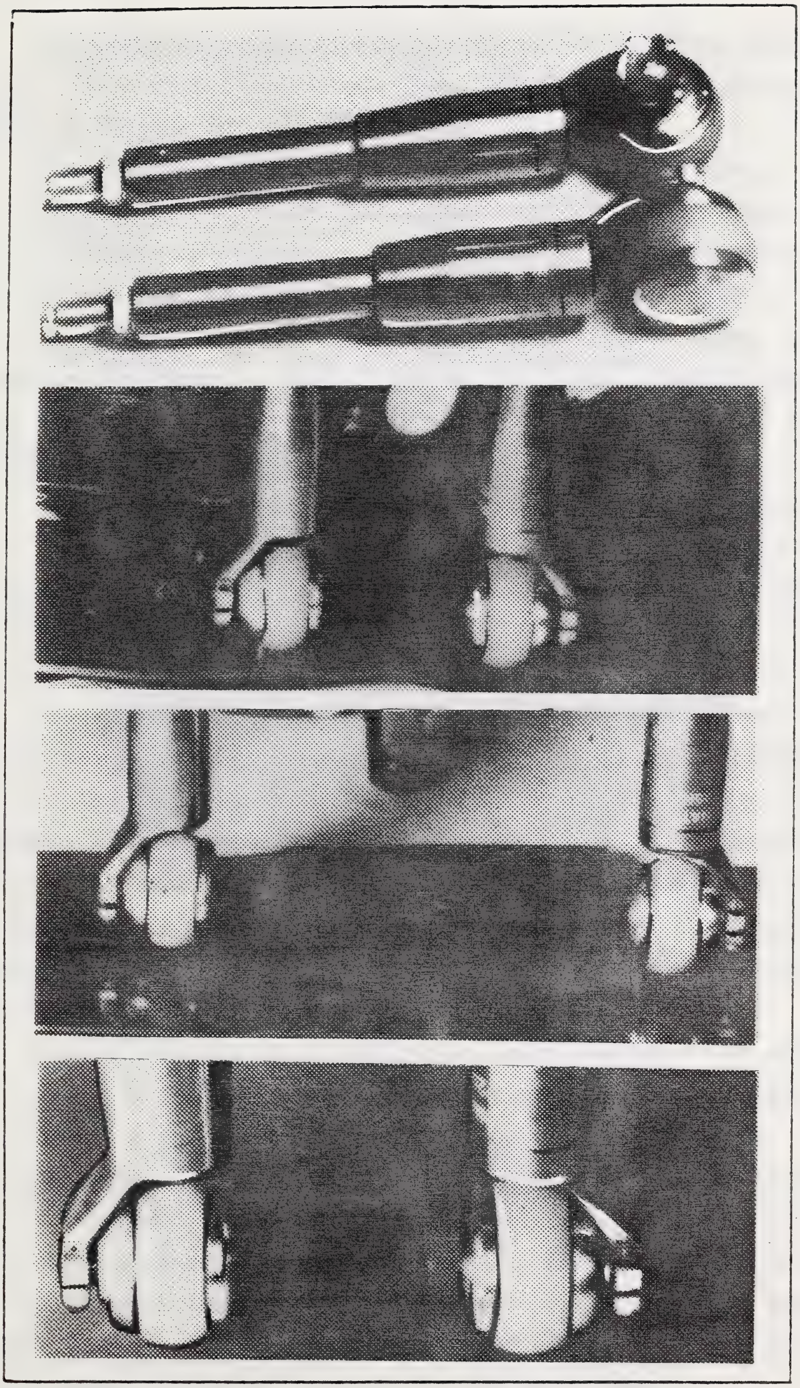


Figure 18. Wheel transducer astride various seam geometries.

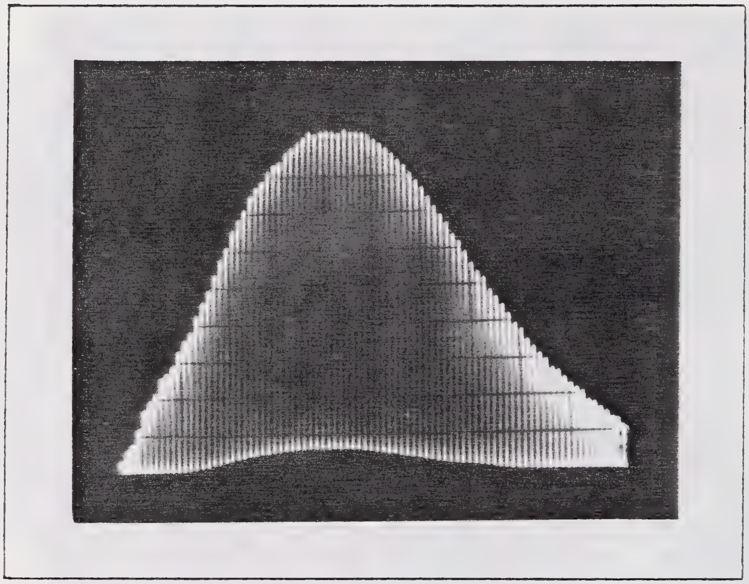


Figure 19. Signal from nondefective membrane.

As defects are encountered the signal is modified, depending on the type and size of defect, until complete lack of fusion eliminates all sound transmission (Figure 20).

The functions of the various controls are as follows:

Range and Multiplier - these controls set the time base range and are calibrated for millimetres of compression wave in mild steel. The set values thus have no absolute significance for polymeric materials.

Delay - provides time base delay by moving all echoes to the left or right across the screen without altering the distance between the echoes. Delay is used on this instrument, with the SET delay facility, to examine a particular signal on an expanded time base.

Delay In-Set-Out - establishes the function of the delay control.

Probe Selection Switch - three-position switch selects operations for single or double pulse echo probes and for dry coupling inspection.

Gain (db) - lower control provides 0 to 90 db of gain in 10 db steps. Upper control provides 0 to 10 db of gain.

Frequency MHz - sets the receiver amplifier band width for optimum test performance, usually to match the peak frequency of the probe being used. The band width values are: 0.1 to 3 MHz, 2.5 to 6 MHz, 4 to 8 MHz, 7 to 18 MHz, W - Wideband. However, in highly attenuative material and operating with pulse echo over long distances where the higher frequencies can be absorbed, or in cases where low frequency noise is troublesome, the band width can be selected to give optimum clarity and resolution irrespective of probe peak frequency.

Reject - this control rejects unwanted low amplitude echoes.

Tune S - for dry coupling application only. Knob rotates to tune the instrument to the probe frequency for optimum transmission.

PRF - this control determines the number of electrical pulses/second applied to the probe, also the number of sweeps/second across the time base of the display screen. For dry coupling, the PRF should be 3000 Hz.

During the inspection procedure the probes were held vertically and positioned just off the edge of each side of the seam (Figure 18). The distance between the probes varied with the seam geometry.

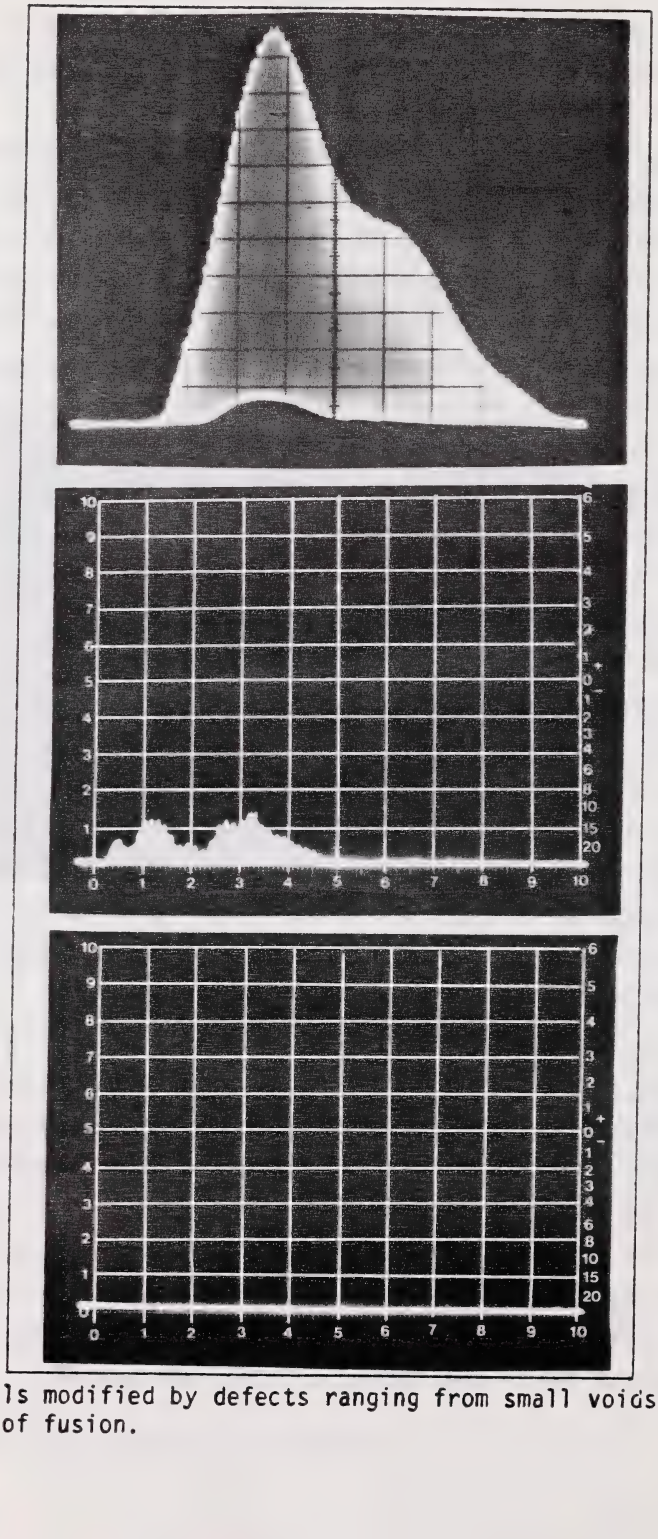


Figure 20. Signals modified by defects ranging from small voids to complete lack of fusion.

As tests proceeded, the effects of varying machine controls such as frequency range, pulse repetition rate, and gain, together with the separation of the probes, were examined.

The general approach with all specimens was to "calibrate" the signal obtained from the membrane alone to full screen height, and then to assess the signal from the seam.

An initial selection of eight seam samples was evaluated without monitoring instrument settings in order to simply observe qualitative differences in the signals on the base liner and the seams. Major differences in signal were ascribed to "defects," and the seams were tested at these locations.

This survey was followed by a more detailed investigation of a few seams to define a standardized procedure.

3. RESULTS

3.1 INITIAL SURVEY

The following samples were surveyed:

1.	Flat extrusion seam	Schlegel	HDPE
2.	Overlap extrusion seam	Gundle	HDPE
3.	Overlap extrusion seam	Schlegel	HPDE
4.	Membrane adjacent to double hot wedge seam. This membrane was known to be defective	Columbia	HDPE
5.	Overlap extrusion seam	Schlegel	HDPE
6.	Dielectric seam	Alta Environment	PVC
7.	Solvent adhesive	Alta Environment	PVC
8.	Thermal fusion seam	Alta Environment	PVC

The results of the ultrasonic inspection, mechanical testing, and microstructural investigation may be found in Section 8.1.

In all instances microstructural defects or rejectable mechanical test behaviour was observed at locations showing ultrasonic indications, but it is also evident that inadequate fusion existed at locations that did not give what we felt to be a significant ultrasonic indication. Conversely, some of the defects that did produce ultrasonic indications would be too small to produce inferior mechanical behaviour, and would thus not affect the service life of the seam.

Three equipment-related factors became apparent during this initial survey:

1. A signal booster is almost a necessity for inspecting seams in membrane less than 1 mm thick. The losses encountered by multiple surface reflections have to be overcome to provide a significantly large transmitted signal. Boosting by a factor of approximately 10 is required.
2. A side-effect of the boosting was a lowering of the frequency about which the input signal is centred. Lower frequencies produced better transmitted signal intensities.

3. The wheel transducer is lacking in design quality both in a mechanical assembly sense and in an electrical sense. The internal oil couplant would leak, the side cover would fall off, abrasion within the wheel support would cause electrical leads to fail, and there was a large amount of electrical noise compared to earlier wheels that have been used. However, it is felt that these difficulties have not affected the substance of the observations made concerning the ability of the equipment to detect significant defects.

3.2 DETAILED SURVEY

These tests were primarily performed on the samples provided by Gundle Lining Systems (Figure 11), since the seam system could not be evaluated using conventional ultrasonic techniques. The thickness of this membrane was 2.0 mm.

Test results and observations are included as Section 8.2. Some results on flat extrusion seams fabricated by Schlegel Lining Technology are also included in this section.

These results again confirm that very small defects can be identified, even small surface crazes. The latter is a very significant observation, since other proprietary work we have done indicates that such crazes are the initial stages of cracks that can slowly propagate to produce brittle fractures over a period as short as three years.

Because of the sensitivity of the technique, small changes within the base membrane can produce variations in the signal. Factors that may affect the signal will include local variations in density, thickness, carbon black content, etc. It is thus necessary when calibrating the signal on the base liner to do so at a typically "good" location. Each manufacturer's material and each thickness of membrane will have its own calibration control settings. However, once the unit has been calibrated, the procedure to detect defects will be the same on each seam geometry.

For 2 mm Gundle HDPE membrane seamed by the overlap extrusion technique, the optimum machine settings and procedures are as follows:

1. Set probes astride the seam and as close as possible;
2. Remove and calibrate on base material at several locations;
3. Set Multiplier at 1.0;
4. Set Range mm at 400;
5. Set Delay at 0.55 (this should set the initial rise of the signal at approximately 2 time base units);
6. Set Gain (db) at 52. [The average peak of the signal should be at Full Scale Height (FSH)]; Fine-tune to ensure mean peak is at 100% FSH;
7. Set Frequency at 0.1 to 3 MHz;
8. Set Reject at 1.0;
9. Set Discriminator x100 KHz at 5.15;
10. Move transducers to seam (increase gain control by 10 db and traverse along the seam, monitor signal); and
11. Reject those areas where the signal remains below 10% FSH.

The Gain setting is a function of material thickness. The Discriminator is a function of material properties and the Delay is a function of seam geometry and distance between the transducers. Unfortunately, the extent of this project is not sufficient to define the relationships between these parameters.

The procedure with the double hot wedge seams that produce two parallel fusion tracks requires two sets of scans to locate specific defects. The first scan will include both fusion tracks between the transducers. If a defect is indicated, a second scan will be required, with the transducer on the overlapped membrane positioned between the two fusion tracks. If the defect no longer appears, it is in the inner fusion track, the one not included between the transducers. Because of the distance between the two transducers when scanning both fusion tracks, it may be necessary to use a booster.

4. DISCUSSION

It is evident that the technique is capable of nondestructively detecting defects in seam geometries that cannot be nondestructively inspected quantitatively with conventional methods. However, much more investigation of signal profiles produced by the different defects is required before the type, number, and distribution of defects can be assessed from the signals observed.

The fundamental question then still remains: What is the critical size and distribution of defects that will cause premature geomembrane failure?

For the present it will be sufficient, and a technological advancement, to reject all seams that produce a signal less than 10% FSH, essentially complete lack of fusion. Some additional effort is required to further define the exact parameters required to ensure that cold fusion is detected.

Several samples examined produced no ultrasonic indications, yet could be peeled apart. The ability to detect cold fusions increases as signal frequency decreases.

A Schlegel flat extrusion seam was known to suffer from cold fusion but, as expected, showed no interface indication when tested by conventional ultrasonic techniques with a signal of 5 MHz. Similarly, no indication was obtained with the flaw detector unit at a frequency setting of W -- the full range of 0.1 to 18 MHz. However, when set at a frequency setting of 0.1 to 3 MHz using the soft-tip probes, the cold fusion was indicated.

This is similar to the observations made on the laminar defects within the membrane itself (Sample #4 of the initial survey). Previous inspections on this material with conventional ultrasonics could not detect the defect that was known not to be a void, but a plane of poor bonding. Inspection at a lower frequency in the present project quite clearly defined the defect.

It is felt that the optimum frequency about which the receiving probe should be centred is 0.3 MHz.

5. CONCLUSIONS

The ultrasonic flaw detector technique using dry scanning wheel transducers at a frequency between 0.1 and 3 MHz is capable of detecting small defects within geomembrane materials and seams to a sensitivity and within seam geometries not possible by other conventional nondestructive techniques.

A procedure has been defined for the ultrasonic inspection of extruded fillet seams in 2 mm thick high density polyethylene geomembranes.

6. RECOMMENDATIONS

1. This procedure should be a required component of the quality control program of all geomembrane installations that involve field seaming, particularly of those installations that contain potentially hazardous wastes.
2. Further information must be generated to relate the observed ultrasonic signal to the nature and distribution of the existing defects.
3. The size and distribution of critical defects must be defined for both instantaneous (immediate) and long-term geomembrane performance.
4. Enforced field inspections would provide the data required for the latter two recommendations, at the same time controlling the seam quality of installed projects.
5. Probes should be designed to operate at a frequency centred at about 0.3 MHz.
6. The design of the probes should be improved to withstand rougher field handling.

7. REFERENCES

Badgerow, D.L. 1983. New development in ultrasonic joint inspection for polyethylene systems. Proceedings of the Americal Gas Association Distribution Conference. Houston, 1983.

Bell, B.S., S. Choland, and L.J. Broutman. 1983. Slow crack growth studies in polyethylene pipe grade resins. Proceedings of the Eighth Plastic Fuel Gas Pipe Symposium. 1983 November 29 to December 01; New Orleans; 57.

Bell, G.R. and D.G. Cook. 1979. Microtoming: An emerging tool for analyzing polymer structures. Plastics Engineering. 1979 August 18 to 22.

House, L.J. and A. Lustiger. 1983. Automated ultrasonic inspection of polyethylene butt fusion joints. Proceedings of the Eighth Plastic Fuel Gas Pipe Symposium. 1983 November 29 to December 01; New Orleans; 74.

Peggs, I.D. 1985. Why quality control? A graphic case history. Proceedings of the Geotechnical Fabrics Conference '85. 1985 June 04 to 05; Cincinnati; 35-42.

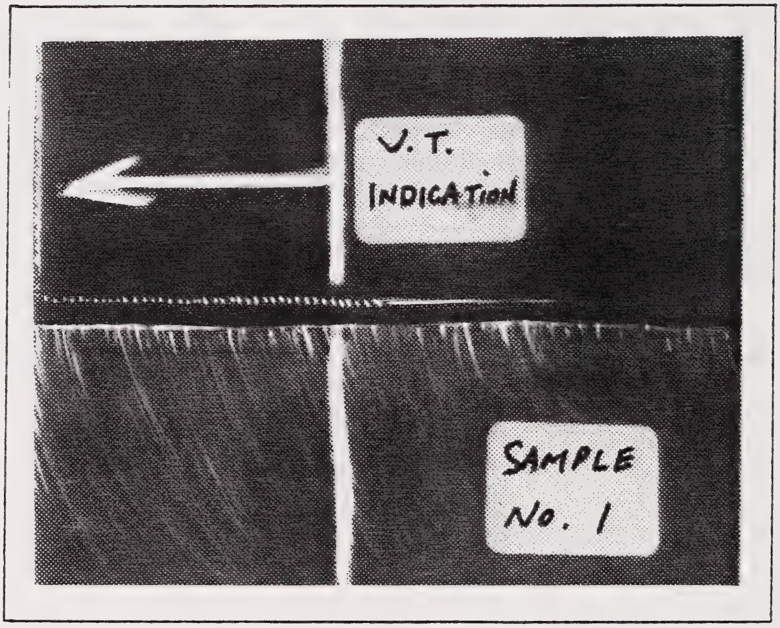
Penttinen, S.E. 1984. Flexible synthetic liners and their use in liquid waste impoundments. Edmonton: Alberta Environment.

8. APPENDICES

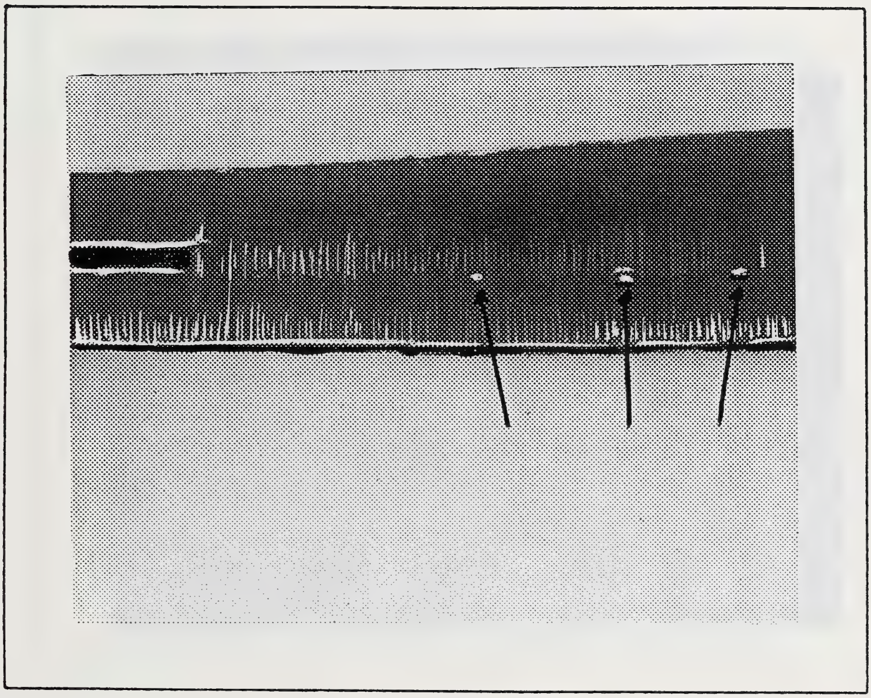
8.1 INITIAL SURVEY

8.1.1 Sample 1

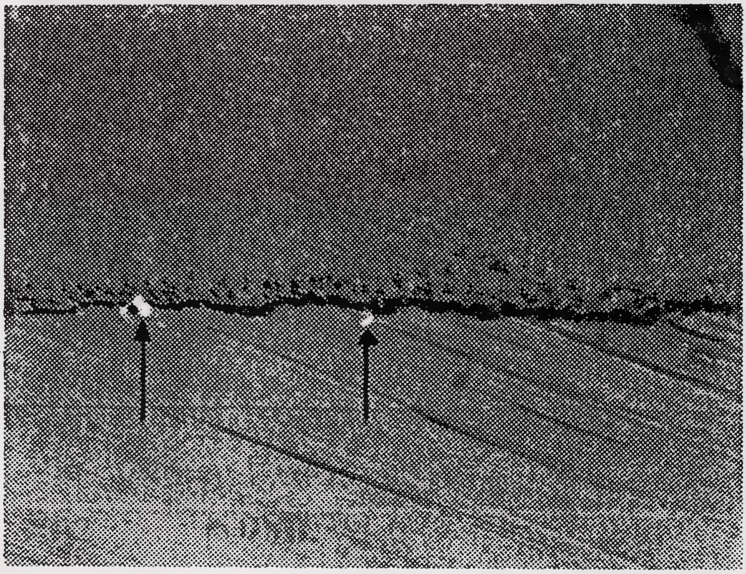
2.0 mm HDPE
Schlegel Flat Extrusion Seam



Ultrasonic indication over 44 mm of seam.



When peel specimens were cut across the seam within the indication; entrapped dirt (indicated with arrows) at the interface was exposed.



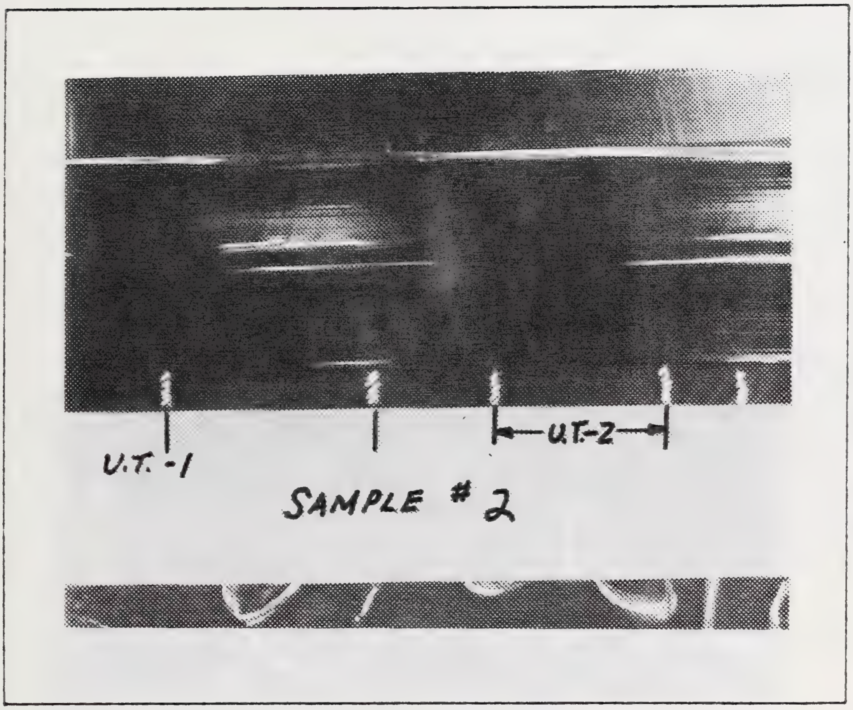
Mag. X 100

A microtome revealed many smaller particles (indicated with arrows) on the interface between the membrane and the extruded deposit.

Despite these observations, the peel specimen did not separate along the fusion line.

8.1.2 Sample 2

1.5 mm HDPE
Gundle Extruded Fillet Seam



Two ultrasonic indications were observed, each about 25 mm along the seam.

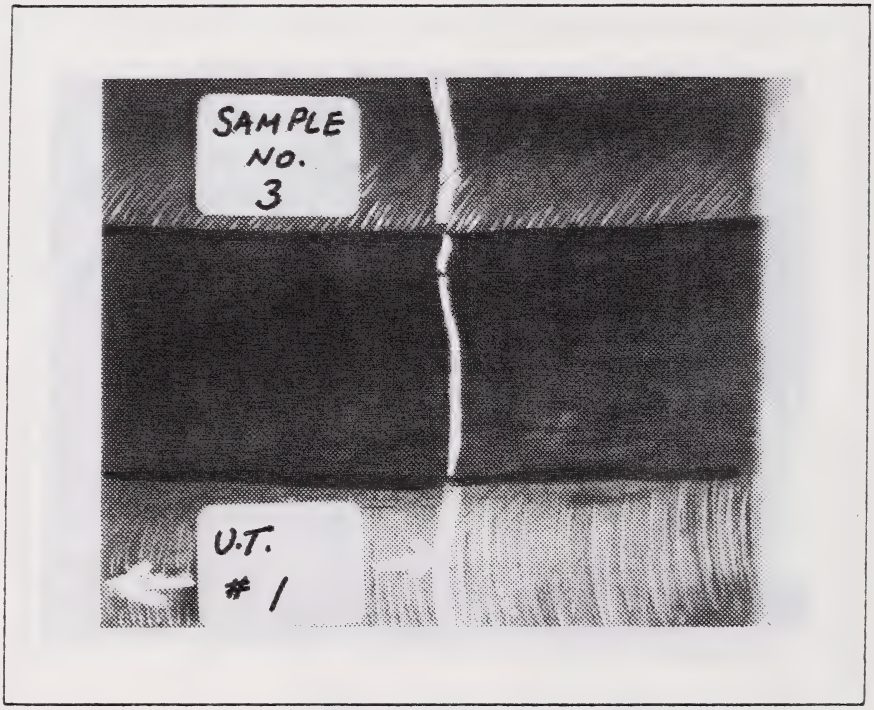
A microtome section showed fine dirt particles on the extruded bead-membrane interface.

Two peel specimens were prepared, one from each indication, and both peeled completely. The seam is of unacceptable quality even though, visually, it appears most satisfactory.

8.1.3 Sample 3

2.0 mm HDPE

Schlegel Extruded Fillet Seam



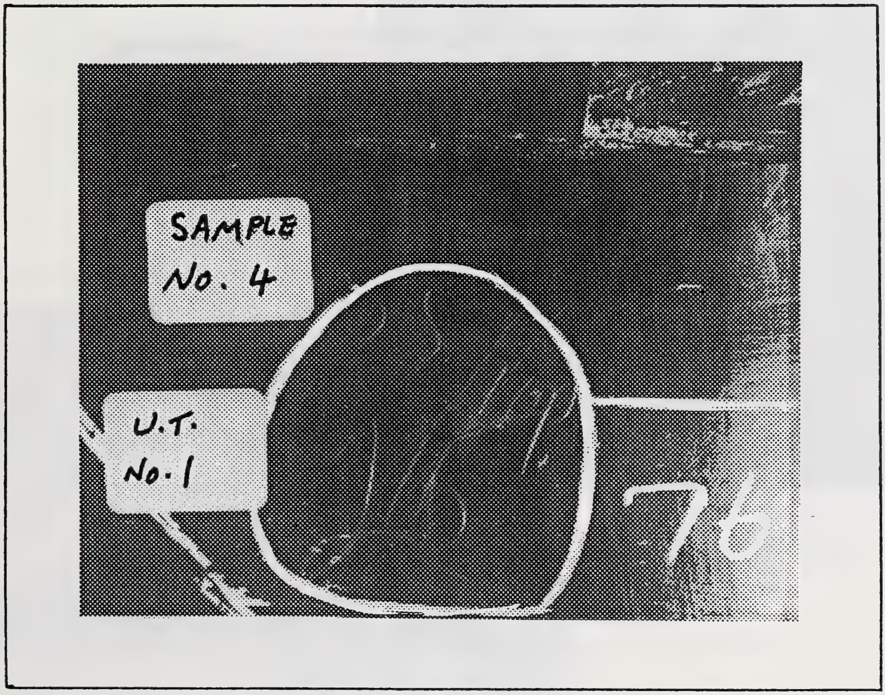
Ultrasonic indication for 55 mm along the seam.

The microtome section again showed sand particles and intermittent poor fusion as evidenced by a distinct interface line.

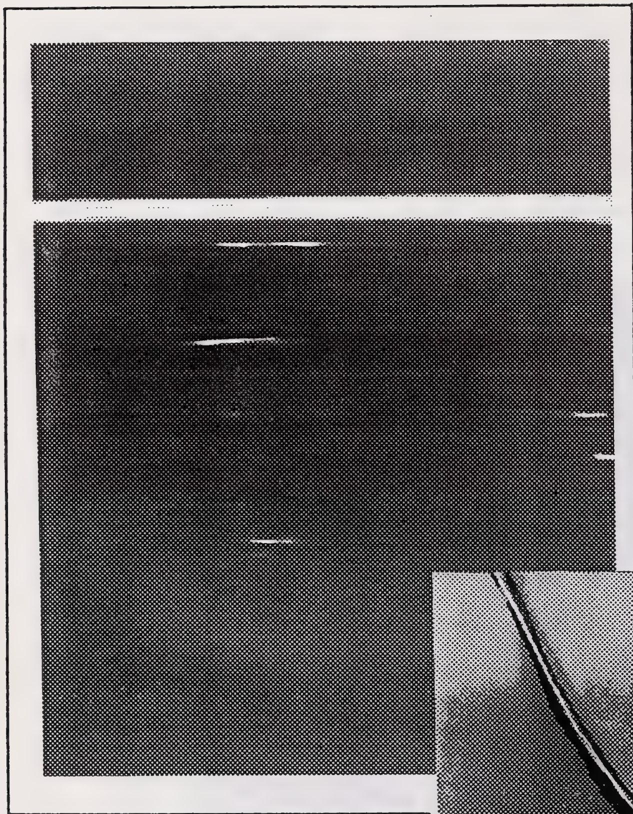
The peel specimen showed 50% peel separation before failing through the membrane. Peel separation in excess of 25% is considered unacceptable.

8.1.4 Sample 4

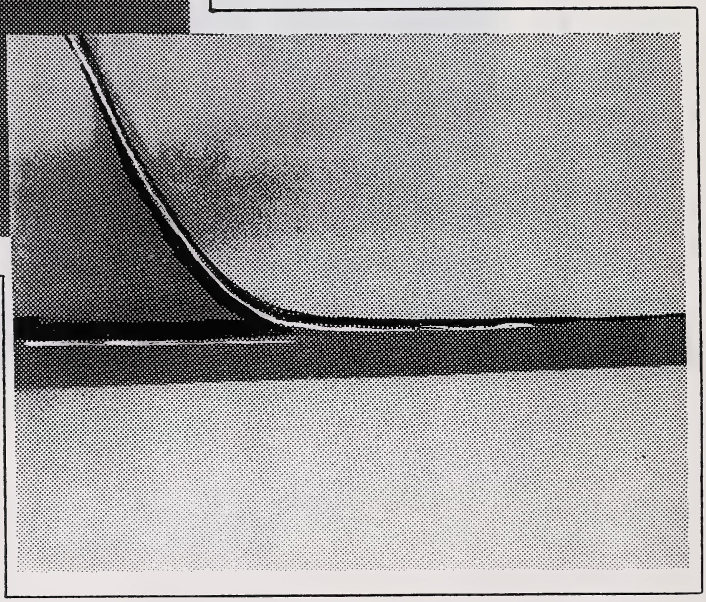
1.5 mm HDPE
Columbia Thermal Wedge Fusion



While calibrating the signal on the membrane, an indication was observed about 50 mm away from the seam. Continuous indications were observed all along the seam.



Mag. X 66.5



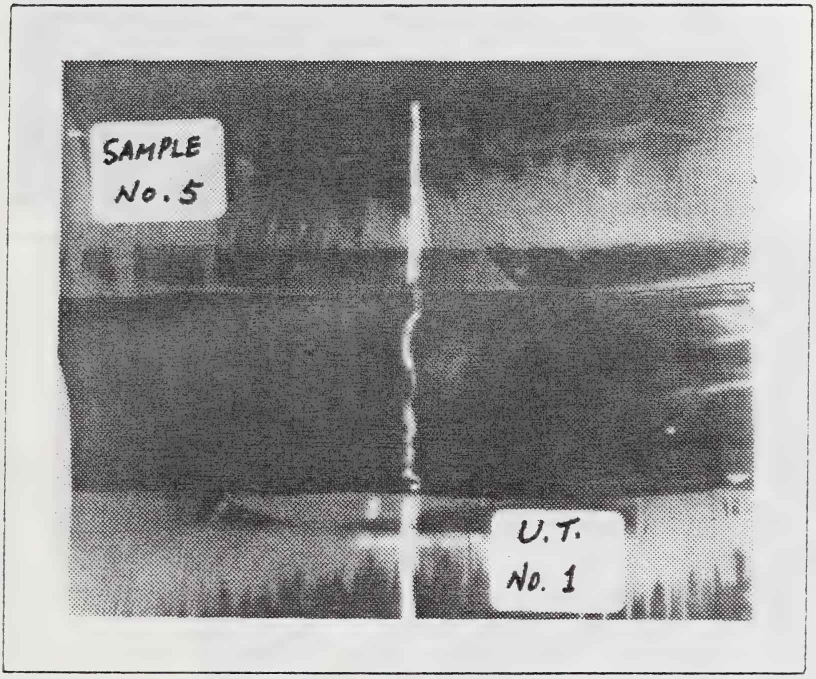
A microtome through the membrane revealed a laminar defect found to be a plane of low bond strength. The membrane could be delaminated along this defect.

Peel specimens peeled completely. Fusion quality was low and very variable.

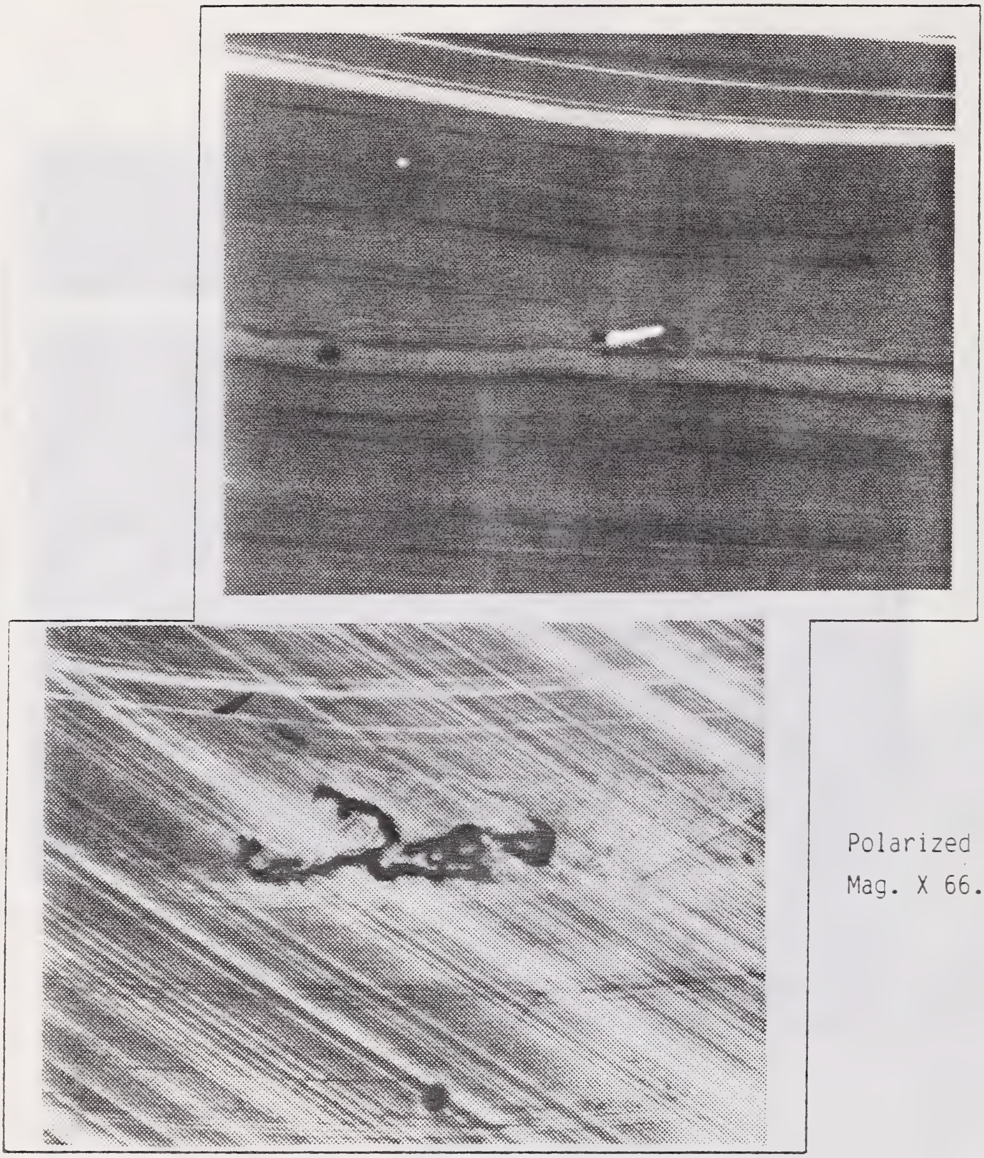
8.1.5 Sample 5

2.0 mm HDPE

Schlegel Extruded Fillet Seam



Two wide ultrasonic indications in a visually acceptable seam.



Polarized Light
Mag. X 66.5

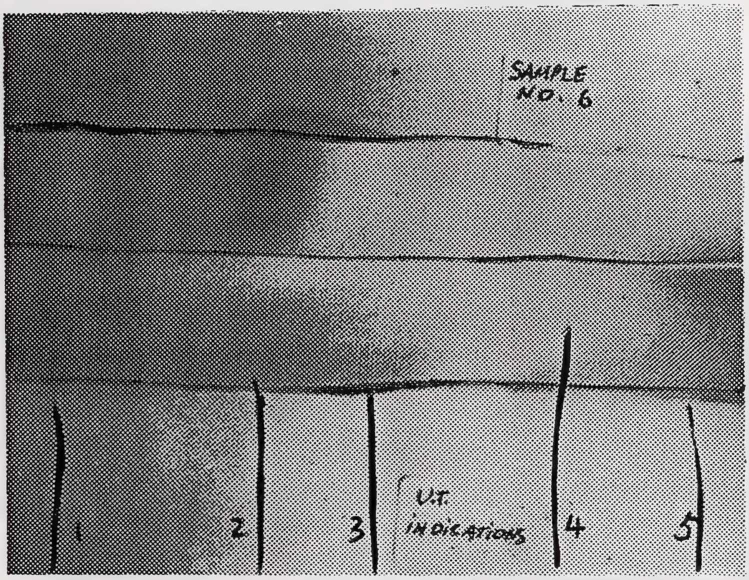
Microtome sections revealed dirt or sand particulates on the fusion interface and fibrous material within the extruded material. Lines indicated with arrows are microtome knife markings. The bars show the width of the extruded material in the bottom photograph.

The peel specimens separated completely. However, a peel specimen prepared from a region that gave no ultrasonic indication also peeled completely.

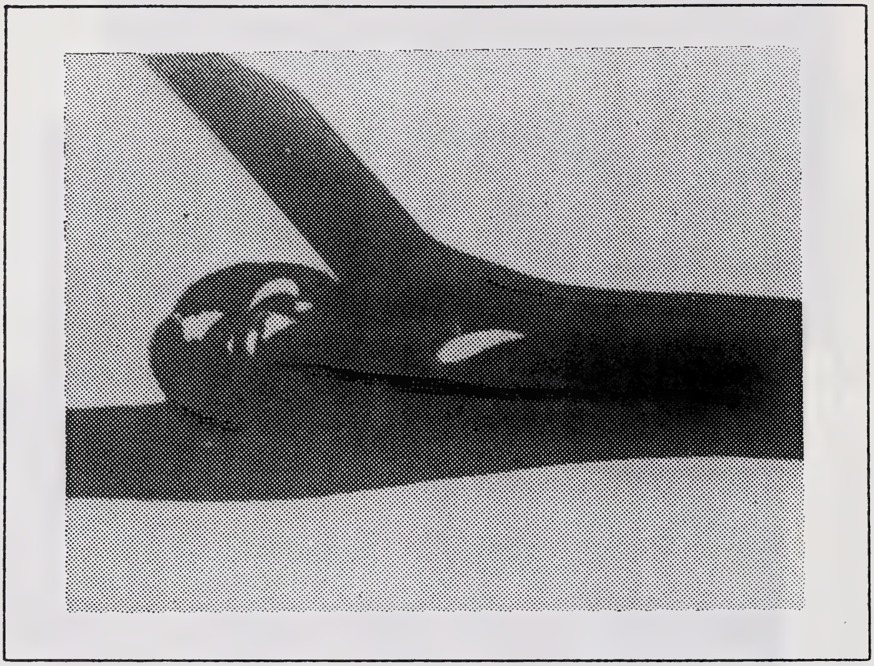
8.1.6 Sample 6

0.55 mm PVC

Dielectric Seam



Several ultrasonic indications along seam.



Mag. X 16.6

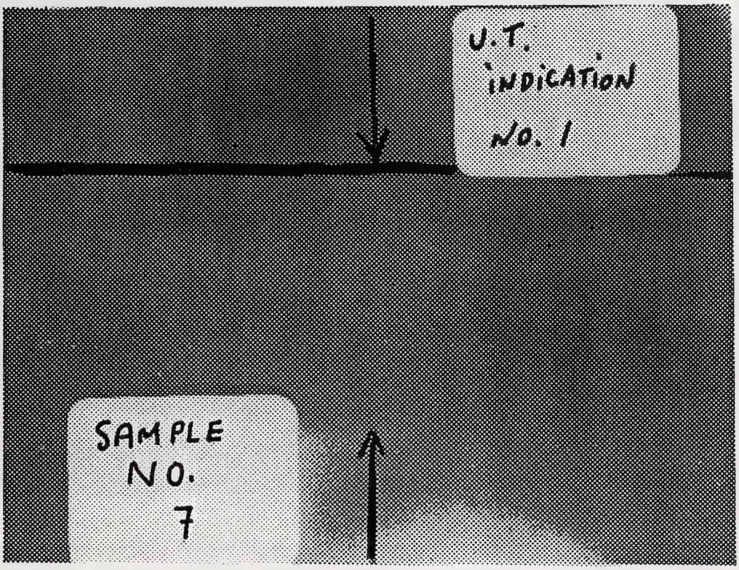
Typical microtome section shows voids within extrudate at edge of seam and a single large void within the fusion zone at the base of the extruded bead. No other defects were identified.

Peel specimens (narrow strips) were cut from each of the five "defective" regions and peel tests performed from each side of the fusion. All specimens failed in the base membrane with zero peel separation.

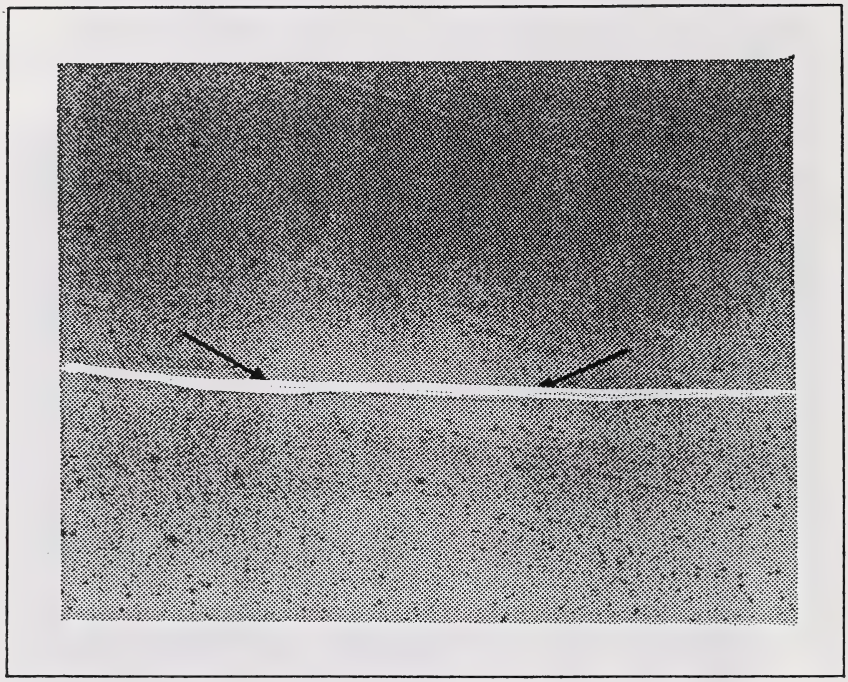
8.1.7 Sample 7

0.5 mm PVC

Solvent Adhesive Seam

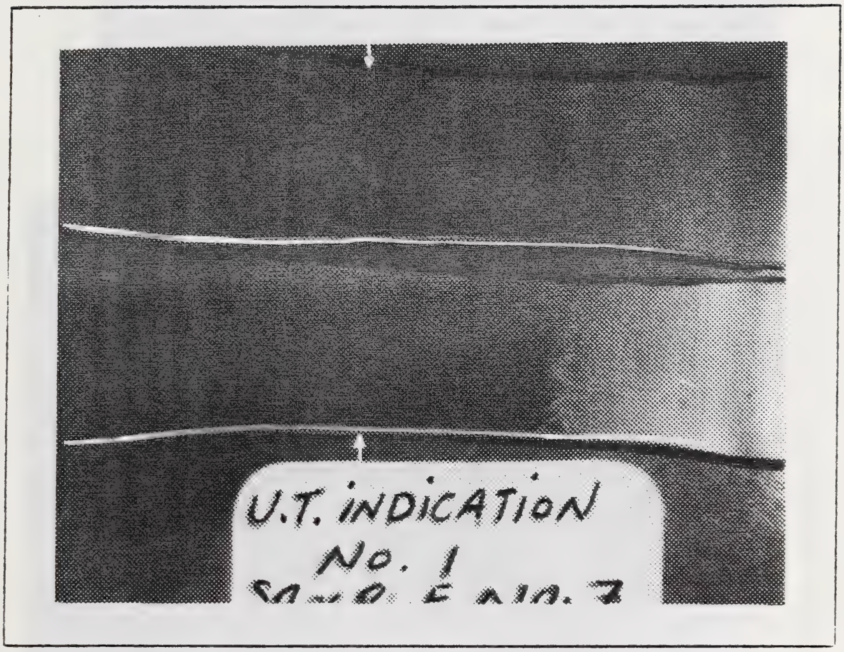


General, variable indications along the length of the seam. Some areas are obviously worse than others.



Mag. X 100

The microtome section shows a distinct interface (white band) where membrane surfaces have not adequately mixed in the solvent. The interface band contains a large void, which is indicated by arrows.



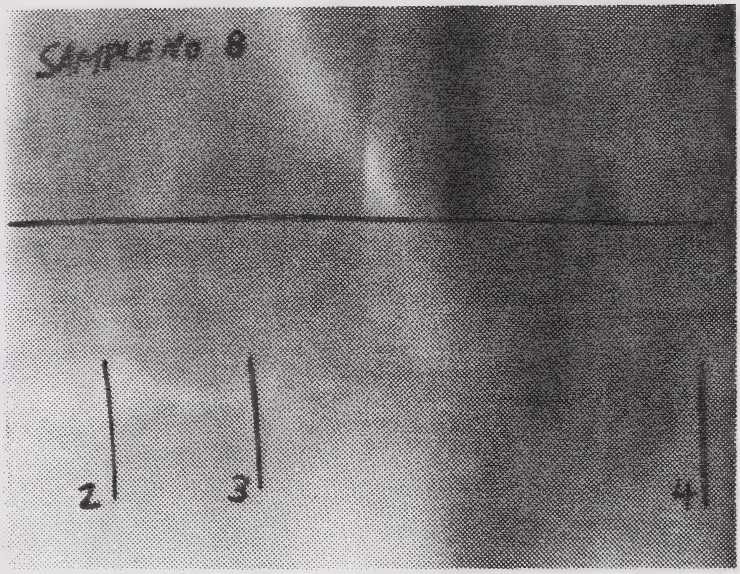
Mag. X 3.2

Peel specimens separated completely, confirming inadequate bond strength and showing the presence of may voids along the centre of the seam.

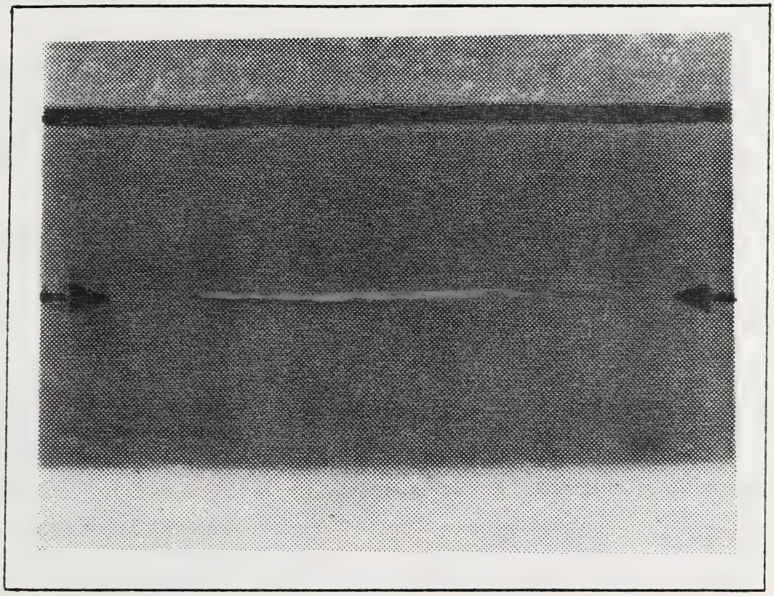
8.1.8 Sample 8

0.5 mm PVC

Thermal Fusion Seam



Four ultrasonic indications noted.



Mag. X 50

Cross-section shows dirt particles on the fusion line, which is indicated by arrows.

The following peel behaviour was observed when specimens were cut from each indication and peeled at both edges of the seam:

Indication	1	0, 25% separation
	2	25, 40% separation
	3	10% separation both sides
	4	25, 40% separation

Only the 40% separations are considered unacceptable. Once again, the defects that produce the indications are not of a size that will result in unacceptable conventional mechanical test behaviour.

8.2 DETAILED SURVEY

8.2.1 Sample Number 1

MANUFACTURER: Gundle
THICKNESS: 2.0 mm
SEAM QUALITY INTENDED: "Good"

MACHINE SETTINGS:

Gain:	59 db	Multiplier:	1.0	Delay:	0.5	Discriminator:	5.50
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

MATERIAL CALIBRATION

Signal height peaks steadily at 100% FSH when roller probes are in motion. Strong signal maintained at gain of 59 dB.

SEAM

Considerable reduction in signal with mean peak at 20% FSH. Most of signal is less than 10% FSH. Increasing the gain by 10 dB increased the signal marginally.

Microtome sections showed prosity within the weld.

A peel specimen from this region failed outside the seam and with no peel separation.

8.2.2 Sample Number 2

MANUFACTURER: Gundle
THICKNESS: 2.0 mm
SEAM QUALITY INTENDED: "Good"

MACHINE SETTINGS:

Gain:	54 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.15
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

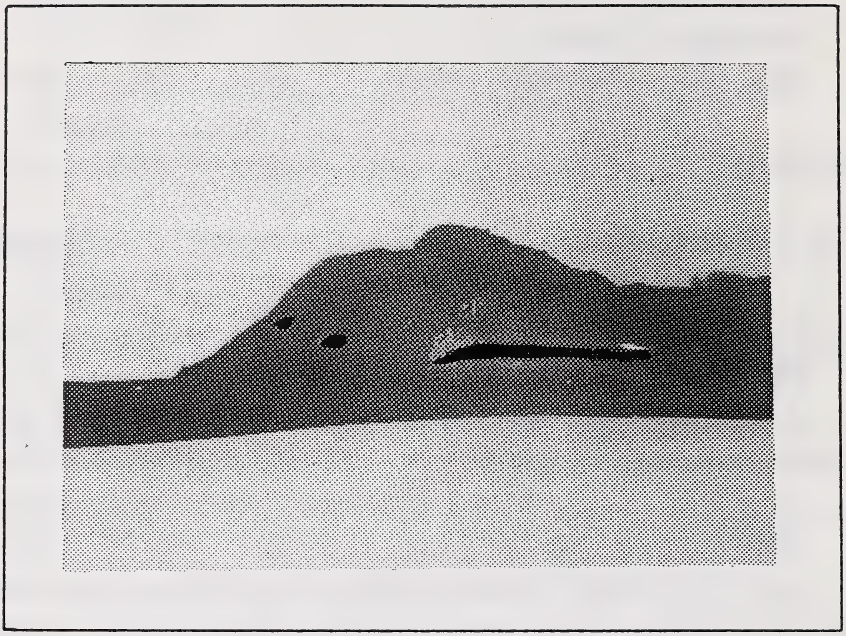
MATERIAL

A strong uniform signal is maintained at 100% FSH with gain set at 54 dB while probes are in motion.

SEAM

Most of the signal reduced to 60% FSH with some areas showing 0%. If the gain is increased by 10 dB the uniform signal can be increased to 100% FSH, but some areas still show 0%.

When sectioned, one of the areas showing no signal was seen to contain small voids in the extrudate and lack of fusion between the extrudate and the edge of the overlapping sheet.



Cross-section that produces no ultrasonic signal at 64 dB gain.

While this amount of porosity is considered to be significant, the peel test showed no peel separation.

SPECIMEN	THICKNESS (mm)	PEEL STRENGTH (MPa)	PEEL SEPARATION %	FAILURE LOCATION
1	2.2	11.6	0	Liner
2	2.18	11.0	0	Liner

Three questions are thus raised:

1. Are existing shear and peel tests adequate for defining substandard seams?
2. Will these defects affect the long-term behaviour of the seam?
3. What tests are required to assess the long-term performance of the seam?

8.2.3 Sample Number 3

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Good"

MACHINE SETTINGS:

Gain:	54 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.19
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

MATERIAL

Uniform signal obtained at 54 dB gain.

SEAM

Most of signal reduced to 40% FSH with some areas down to 10%. An additional 10 dB gain would increase the signal to 80% FSH.

Voidage similar to that shown in Sample 2 was present at those areas giving 0% signal.

Peel test specimens from these areas did not separate.

8.2.4 Sample Number 4

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Good"

MACHINE SETTINGS:

Gain:	52 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.11
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

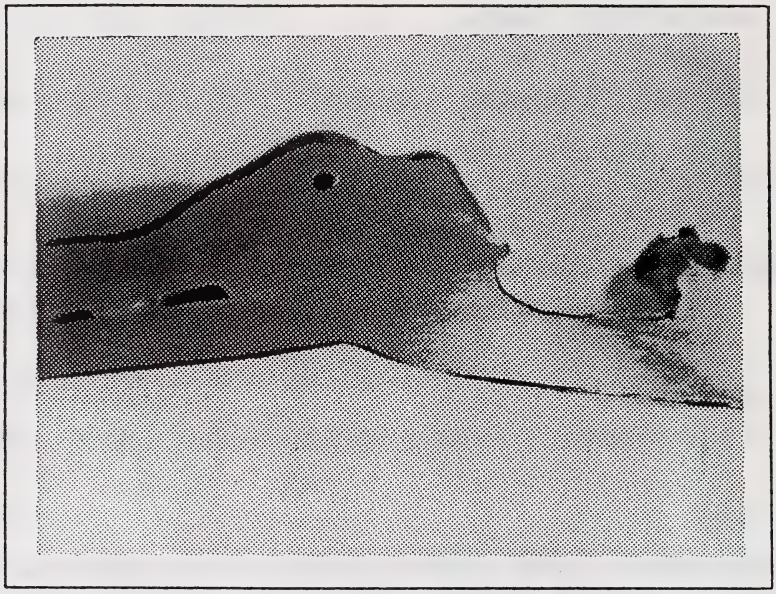
MATERIAL

A gain setting of 52 dB produces a uniform signal at 100% FSH.

SEAM

Most of the signal reduced to 40% FSH with some areas less than 10% FSH. A gain increase of 10 dB is required to boost 40% signal to 100%, while those areas at 10% move up to 40%. A few areas remain unchanged at 0% FSH.

Close to these regions some porosity is evident.



Mag. X 10

Porosity in defect-indicated region.

The porosity cannot cause a complete loss of the ultrasonic signal. Additonal porosity or poor fusion would be expected in adjacent regions to produce a 0% FSH signal. These areas must be very localized since poor behaviour was not observed using 25 mm wide strips.

SPECIMEN	THICKNESS (mm)	PEEL STRENGTH (MPa)	PEEL SEPARATION %	FAILURE LOCATION
1	2.17	11.7	0	Liner
2	2.12	12.0	0	Liner
3	2.20	9.7	0	Liner

There were relatively heavy grinding marks on the liner adjacent to the weld deposit that may affect the UT signal and be responsible for the low strength value of 9.7 MPa.

8.2.5 Sample Number 5

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Indifferent"

MACHINE SETTINGS:

Gain:	57 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.28
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

MATERIAL

A strong signal peaking at 100% FSH but with an average intensity at 90% FSH was obtained at a gain setting of 57 dB.

SEAM

Signal reduced to 20% FSH uniformly which could be increased to 80% FSH by increasing gain 10 dB.

Peel specimens cut from each end of this sample failed away from the weld.

SPECIMEN	THICKNESS (mm)	PEEL STRENGTH (MPa)	PEEL SEPARATION %	FAILURE LOCATION
1	2.00	9.7	0	Liner
2	1.99	9.0	0	Liner
3	2.01	10.7	0	Liner

8.2.6 Sample Number 6

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Indifferent"

MACHINE SETTINGS:

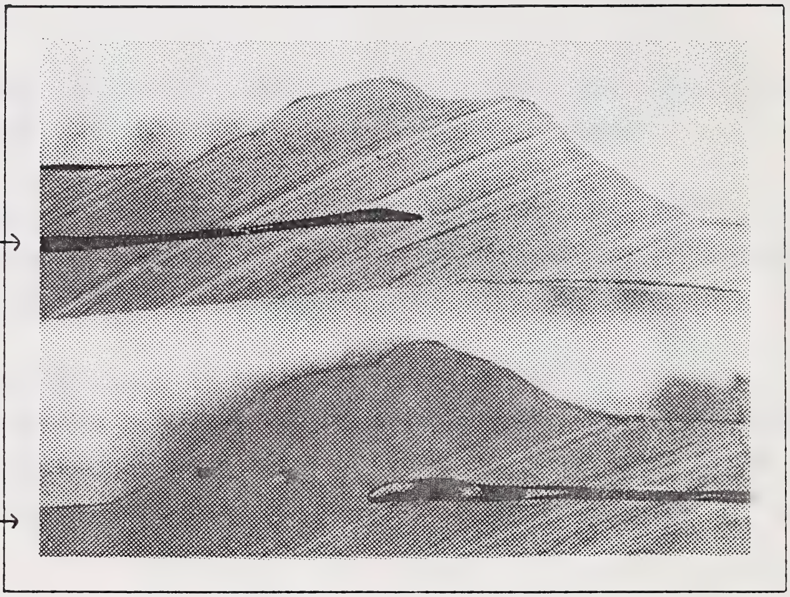
Gain:	57 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.30
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

MATERIAL

100% signal at 57 dB gain.

SEAM

Mostly at 80% FSH with a few areas as low as 5% FSH. Porosity is again evident at the 5% regions, but peel specimens tested from both areas all showed satisfactory behaviour by failing away from the seams.



Seam cross-sections that produce 50% FSH signal (top) and 5% FSH signal (bottom).

8.2.7 Sample Number 7

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Indifferent"

MACHINE SETTINGS:

Gain:	59 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.30
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

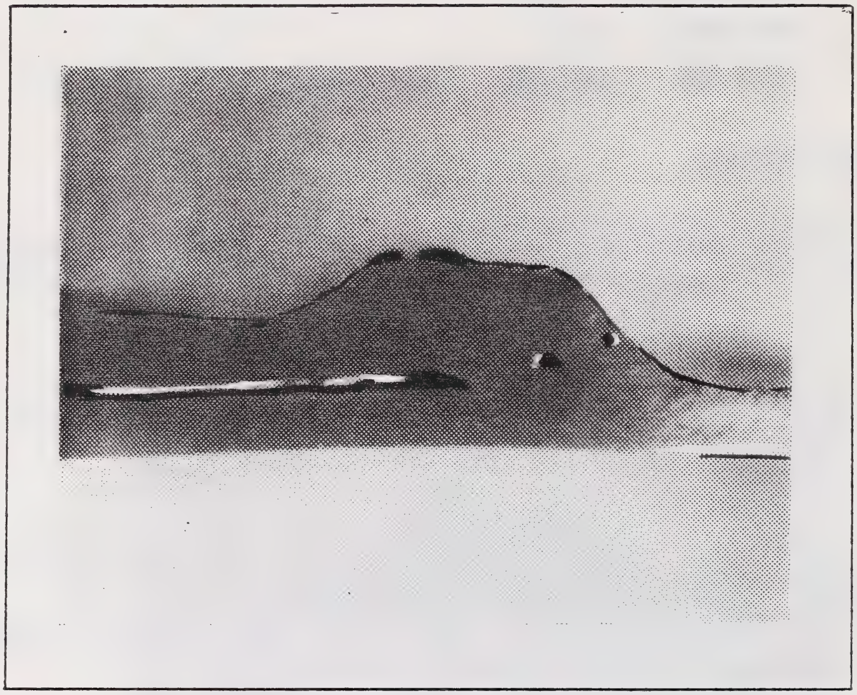
MATERIAL

Signal at 100% FSH obtained with gain at 59 dB.

SEAM

Most of the specimen showed a 10% FSH signal, with only a few areas at a maximum of 40% FSH.

Porosity within the weld deposit and at the edge of the overlapping sheet was evident, similar to Sample 2.



Mag. X 10

Porosity within Sample 7.

Two peel strength values were marginally low.

SPECIMEN	THICKNESS (mm)	PEEL STRENGTH (MPa)	PEEL SEPARATION %	FAILURE LOCATION
1	2.00	11.8	0	Liner
2	1.98	9.2	0	Liner
3	2.01	9.1	0	Liner
4	1.99	10.4	0	Liner

8.2.9 Samples Number 9 and 10

MANUFACTURER: Gundle

THICKNESS: 2.0 mm

SEAM QUALITY INTENDED: "Poor"

MACHINE SETTINGS:

Gain:	50 dB	Multiplier:	1.0	Delay:	0.55	Discriminator:	5.10
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

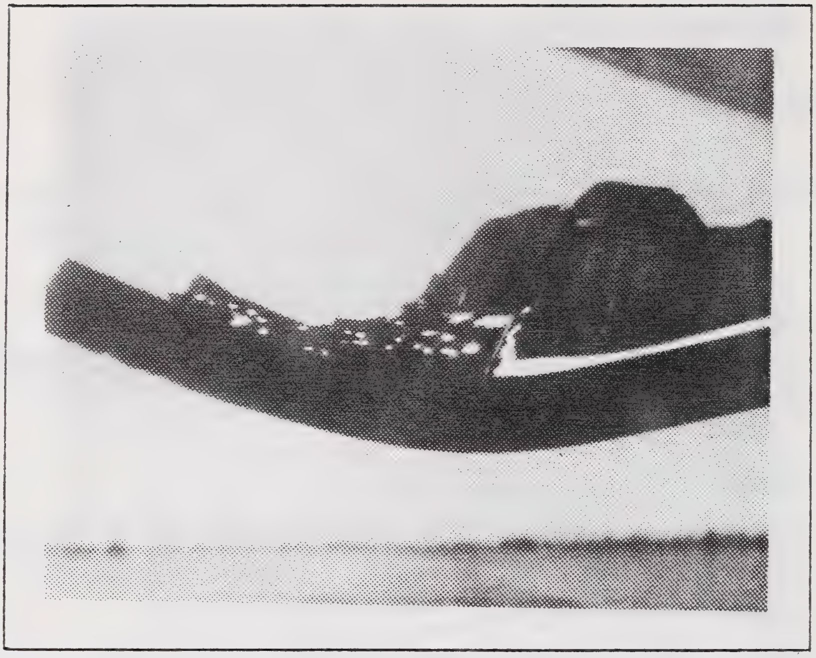
MATERIAL

Signal was uniformly greater than 100% FSH, even with gain turned down to 50 dB.

SEAM

Maximum at any location was 10% FSH. At 58 dB, an increase of 8 on the gain control, the 10% response could be increased to 50% FSH, but most of the other areas did not increase.

Large amounts of prosity were evident in the areas that showed no ultrasonic signal.



Sample 10. Porosity that causes complete loss of ultrasonic signal.

Peel specimens prepared from these samples showed very low peel strengths and complete peel separation.

SPECIMEN	THICKNESS (mm)	PEEL STRENGTH (MPa)	PEEL SEPARATION %	FAILURE LOCATION
1	2.20	9.6	100	Weld
2	2.20	4.1	100	Weld
3	2.22	2.2	100	Weld

8.2.10 Sample Number 11

MANUFACTURER: Schlegel

THICKNESS: 2.5 mm

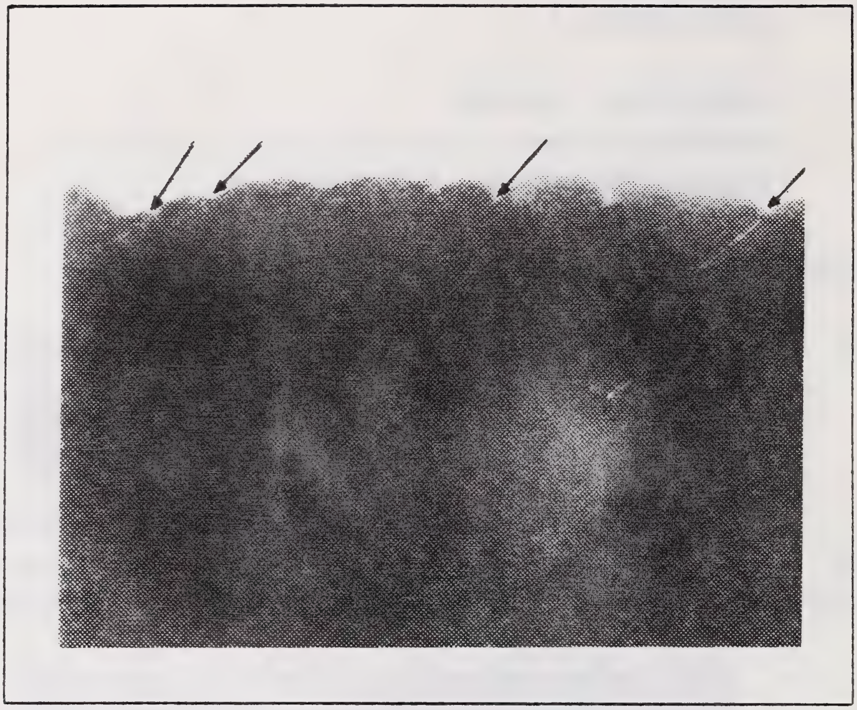
SEAM QUALITY INTENDED: "Average"

MACHINE SETTINGS:

Gain:	53 dB	Multiplier:	1.0	Delay:	0.50	Discriminator:	5.25
		Range	400	Frequency:	0.1-3.0	Reject:	1.0

MATERIAL

A uniform signal at 100% FSH was obtained at a gain setting of 53 dB. However, a reduced signal was obtained in one local area that, when sectioned and microtomed, revealed crazing at small surface defects.



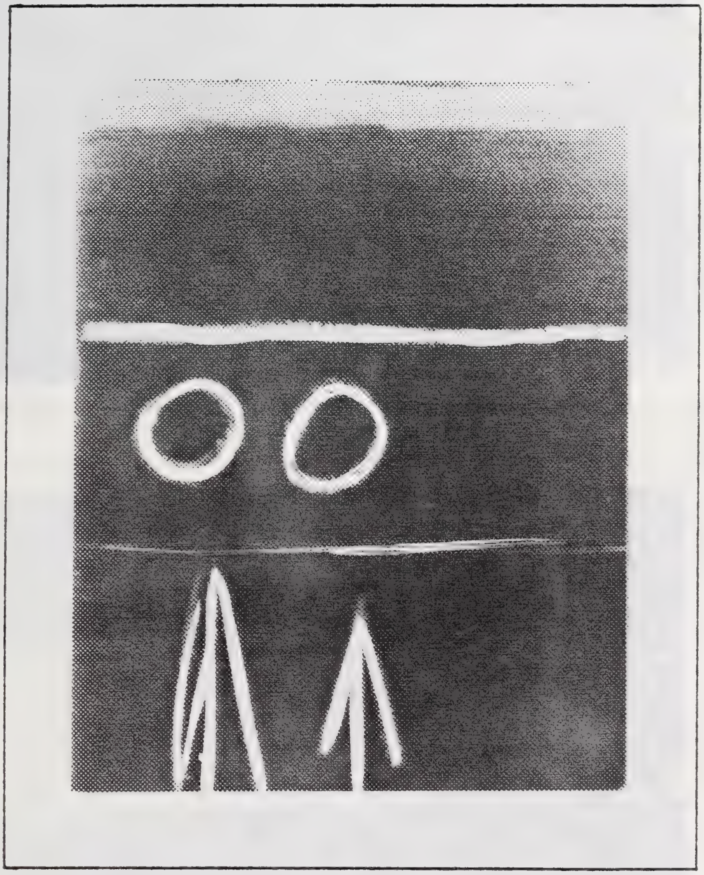
Mag. X 200

Surface crazing marked with arrows at stress-concentrating sites on surface of base membrane.

Such crazes are the forerunners of physical cracks and have been observed within seams at stress concentrating surface profiles and on poorly fused surfaces that have been peeled apart.

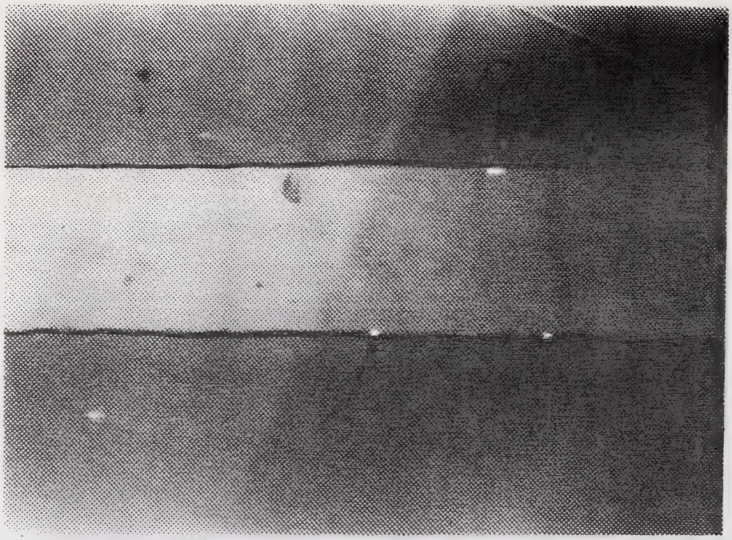
SEAM

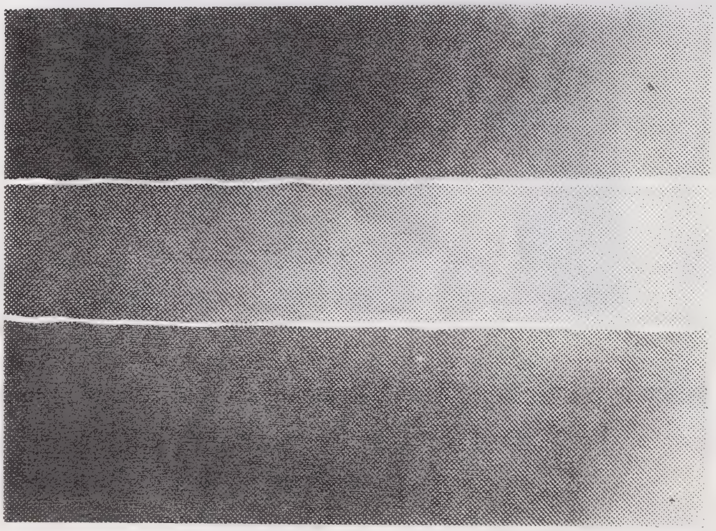
At the 53 dB gain setting a reduction in signal height to 70% FSH was obtained, with one region about 50 mm long showing a more significant reduction. This region was surveyed with a conventional 5 MHz transducer and two defect regions were isolated.



Isolated regions giving ultrasonic indications by both conventional and flaw detection techniques.

Microtomes prepared from these regions and "acceptable" regions of the seam show the former to contain several small voids at the extrudate-membrane interfaces.





Away from V.T. Indication

Mag. X 90

Microtome showing voids (circled) on interface that produce ultrasonic indication, top. Area of "acceptable" fusion is at bottom.

Peel specimens prepared from these regions showed acceptable behaviour.

This inspection clearly shows the ability of the technique to define the presence of very small defects both on the surface of the membrane and within the seam itself. However, neither of these defects is defined by conventional mechanical testing. While the voids within the seam may be of no significance in the long-term performance of the membrane installation, the surface crazes undoubtedly will be.

The crazes will undoubtedly initiate cracks under tensile loading, which will propagate in a brittle manner until complete membrane penetration occurs.

8.3 GENERAL COMMENT

The fact that a strip specimen successfully passes a peel test does not necessarily indicate that fusion is satisfactory across the full width of the seam. Several seaming techniques produce seams where the degree of fusion decreases from the underside edge where the peel test is performed to the opposite edge which is exposed to the contained fluid. Thus, a "back peel" test at this exposed edge could result in peel separation back toward the edge that is satisfactorily fused.

Consequently, a significant ultrasonic defect indication with satisfactory conventional peel behaviour are not inconsistent.

8.4 SUMMARY

For the Gundle specimens the control settings are summarized as follows when calibrating the base material:

SAMPLE	GAIN,dB	MULTIPLIER	RANGE	DELAY	FREQUENCY	DISCRIMINATION	REJECT
1	59	1.0	400	0.50	0.1-3.0	5.50	1.0
2	54	1.0	400	0.55	0.1-3.0	5.15	1.0
3	54	1.0	400	0.55	0.1-3.0	5.19	1.0
4	52	1.0	400	0.55	0.1-3.0	5.11	1.0
5	57	1.0	400	0.55	0.1-3.0	5.28	1.0
6	57	1.0	400	0.55	0.1-3.0	5.30	1.0
7	59	1.0	400	0.55	0.1-3.0	5.30	1.0
8	54	1.0	400	0.55	0.1-3.0	5.25	1.0
9	50	1.0	400	0.55	0.1-3.0	5.10	1.0
10	50	1.0	400	0.55	0.1-3.0	5.10	1.0
11	50	1.0	400	0.55	0.1-3.0	5.10	1.0

When the probes are transferred to the seam, an increase in gain of approximately 10 dB is required to improve sensitivity to more clearly define seriously defective regions.